GSFC · 2015

Thermal Design Parameters and Case Studies: *The Low Density Supersonic Decelerator (LDSD) Project – A High Altitude Balloon Mission*

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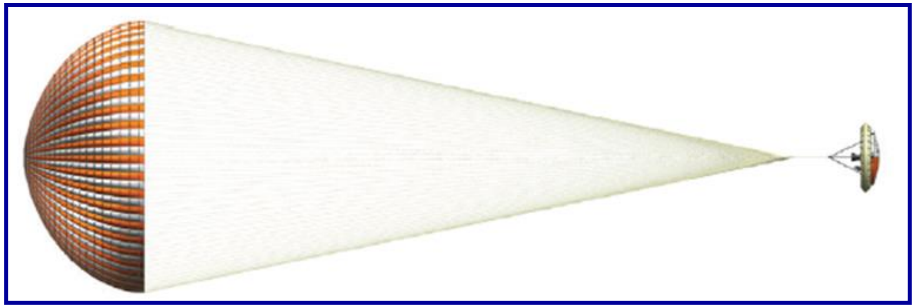
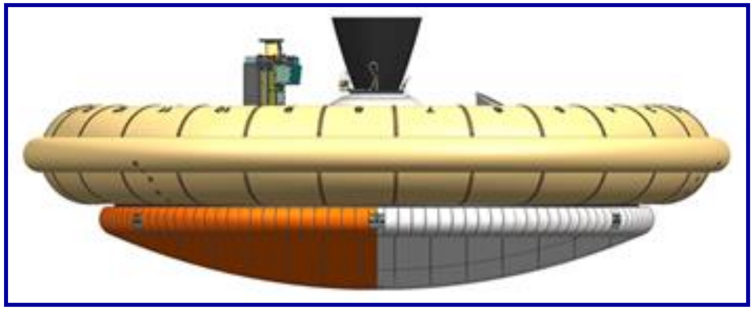
Course Description

This short course will present a brief introduction into the parameters that affect thermal design. Two case studies showing how the thermal design evolves from the mission specific requirements will be given. The first case study presented by **Carol Mosier** is for the Cosmic Background Explorer (COBE) spacecraft and instruments. The COBE mission, which proved the big bang theory, utilized cryogenic instruments that needed to be colder than space to collect the required science data. The resulting design and thermal challenges will be highlighted.

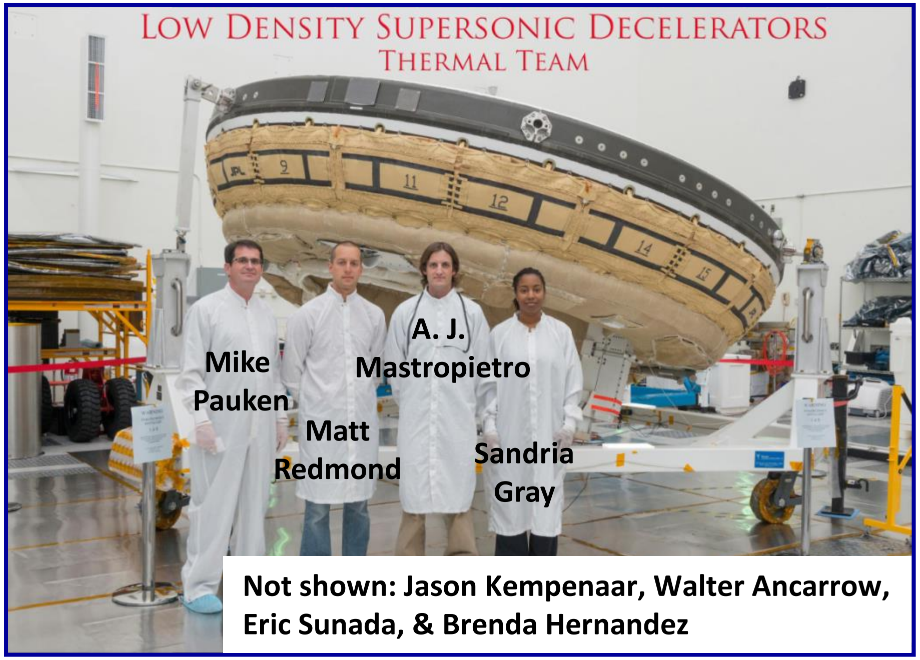
The ***second case study*** is for the ***Low Density Supersonic Decelerator (LDSD) Supersonic Flight Dynamics Test (SFDT) vehicle***. The SFDT vehicle's thermal control system had to protect avionics, batteries, cameras, data recorders, and the composite core structure during a freezing cold balloon assisted ascent as well as during a solid rocket powered flight which posed a high heating environment. An introduction to NASA's LDSD technology demonstration program and a brief review of the thermal design and analysis of the test vehicle including bounding environments will be presented along with some of the thermal telemetry from the first flight followed by several hard lessons learned.





Instructor Bio

A. J. Mastropietro is currently a Thermal Systems Engineer at NASA's Jet Propulsion Laboratory where he was most recently the Lead Thermal Engineer on the Low Density Supersonic Decelerator (LDSD) Project which had its first successful stratospheric test flight in June 2014. Prior to that assignment, A. J. was also a key member of the Mars Science Laboratory's (MSL) Heat Rejection System (HRS) Thermal Team that was responsible for implementing the world's first and only Martian Mechanical Pumped Fluid Loop now operating continuously for over 2.5 years onboard the Curiosity Rover. Presently, A. J. is serving as the Thermal Systems Engineer for the recently announced mission to Jupiter's icy moon Europa.



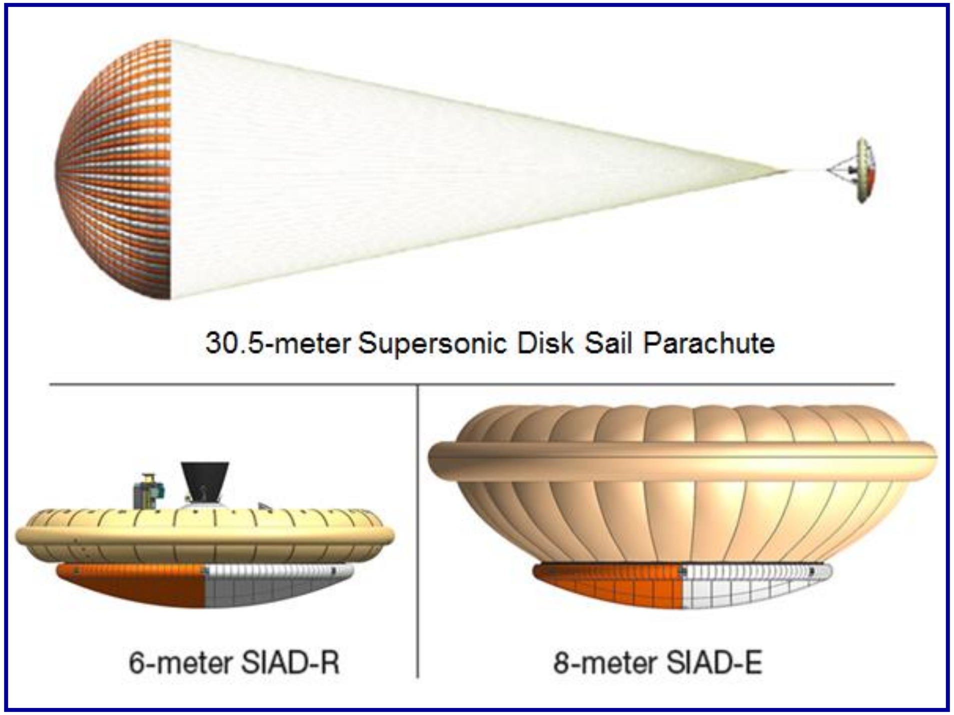
Agenda

- Part 1 Introduction
  - LDSD Project Overview – A High Altitude Balloon Mission
  - SFDT Vehicle Description and Thermal Challenges
- Part 2 LDSD Thermal Analysis
  - SFDT Thermal Environments
  - SFDT Thermal Model
  - SFDT Bounding Mission Cases
  - Thermal Analysis of the Electronics Pallet Assembly
  - Thermal Analysis of the Core Structure Assembly (CSA)
  - Thermal Analysis of the Main Motor Mount
  - Thermal Analysis of the Spin Motors
  - Thermal Material Property Measurements
- Part 3 SFDT-1 Flight Test Results
  - Day of Test Thermal Environment, Trajectory, and Timeline
  - SFDT-1 Key Events
  - SFDT-1 Thermal Telemetry (Select Components)
  - Post-Flight Visual Inspection of the Recovered TV
- Lessons Learned and Conclusions

Part 1
Introduction

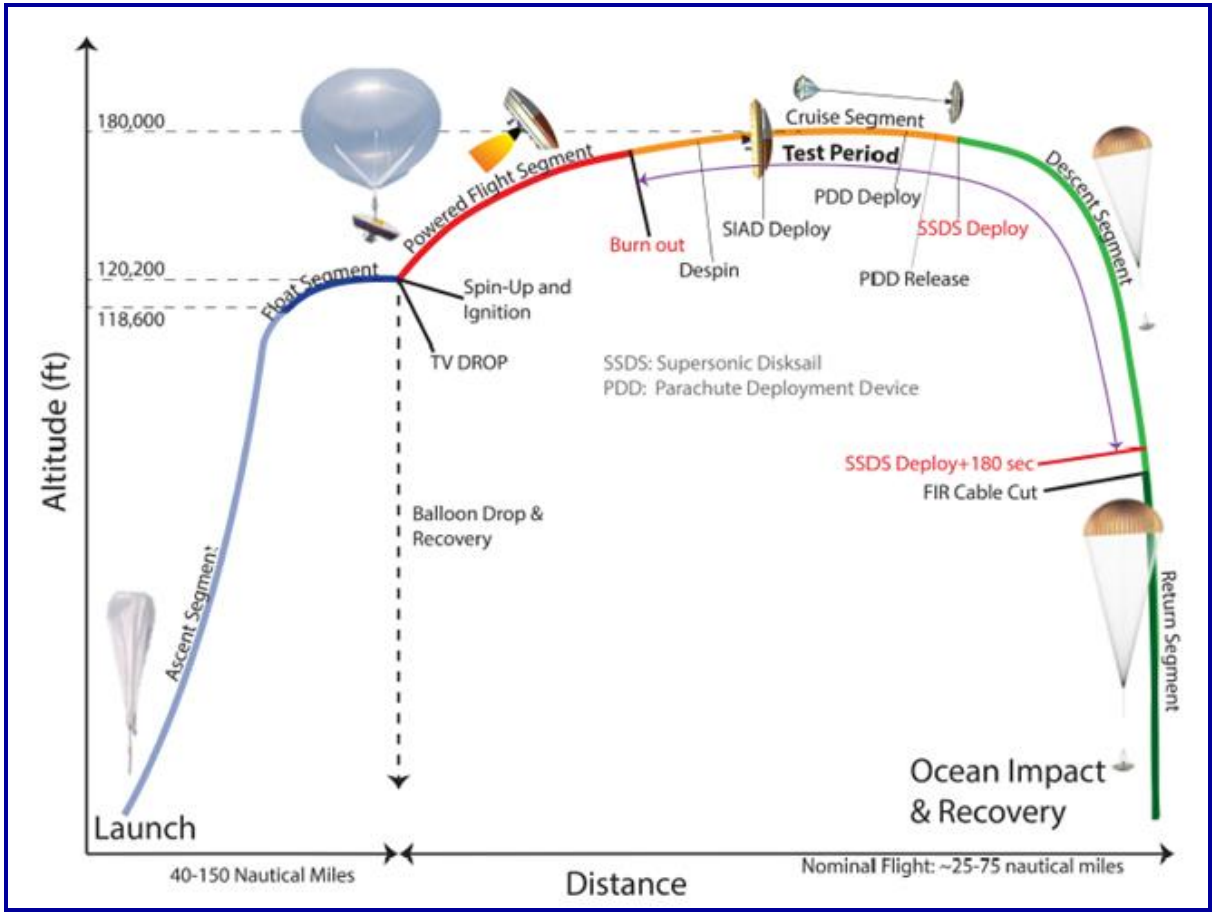
LDSD Project Overview (1/2)

- Charged by NASA's Office of the Chief Technologist to advance the state of the art for Mars EDL
- 3 new EDL technologies under development
  - 30.5 m diameter Disk Sail Parachute
  - Robotic Class SIAD (6 m torus)
  - Exploration Class SIAD (8 m isotensoid)
- Supersonic Flight Dynamics Test (SFDT) Vehicle will provide the experimental platform for testing these new technologies
- Stratospheric tests using helium carrier balloons occurred during the summers of 2014 and 2015 at the PMRF on Kauai, Hawaii

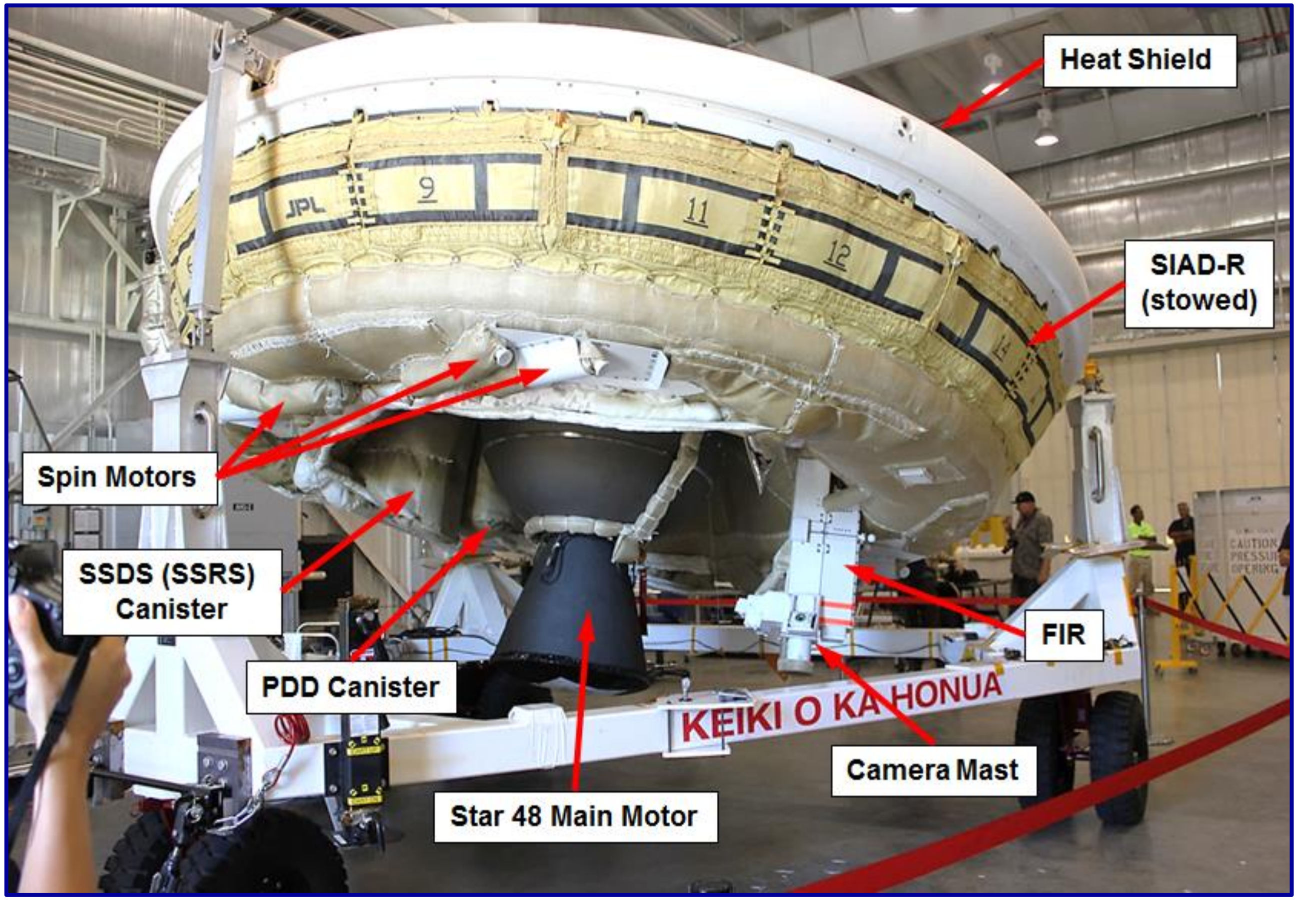


Supersonic **I**nflatable **A**erodynamic **D**ecelerator (**SIAD**)

Proposed Flight Profile for High Altitude LDSD Tests using the SFDT Vehicle



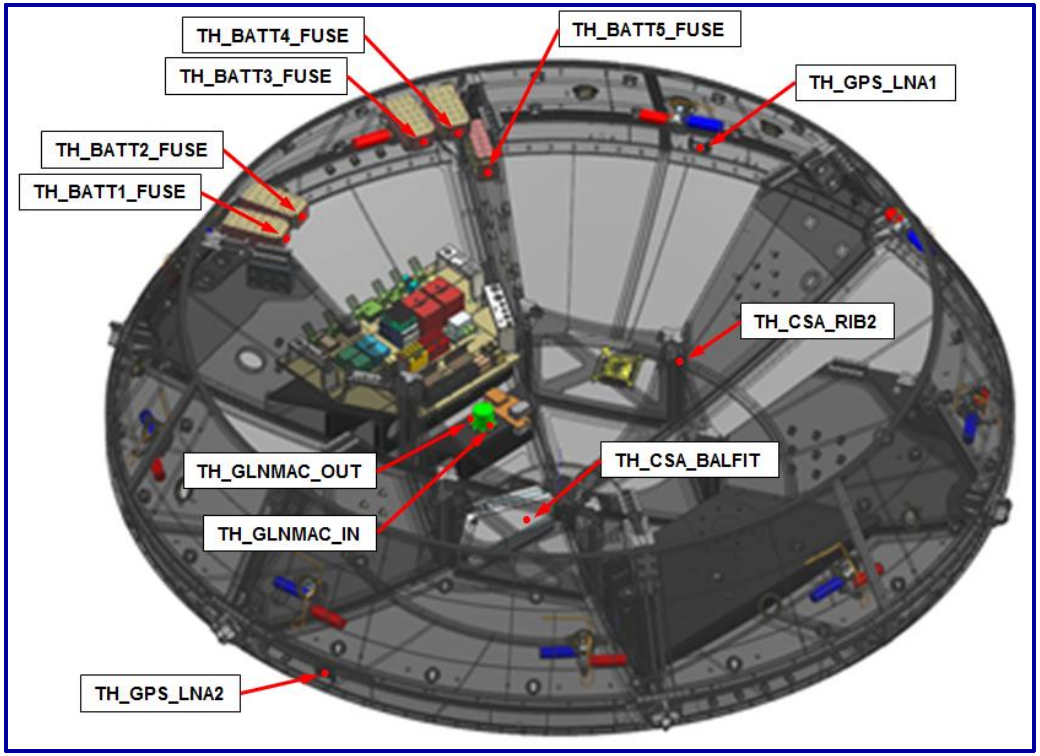
SFDT Vehicle Description (External)



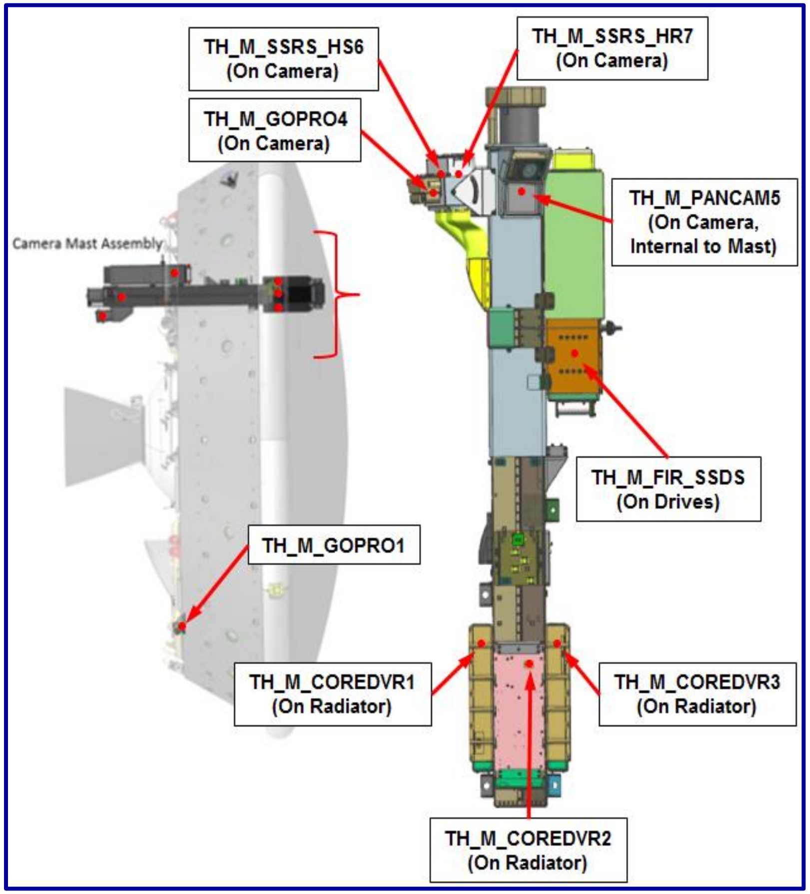
<u>Note 4 major thermal challenges</u>: 1) Star 48 plume heating, 2) Star 48 soakback heating, 3) Spin Motor plume heating, and 4) Spin motor soakback heating

Additional thermal challenges were:

Avionics Pallet and GLNMAC



Camera Mast Assembly

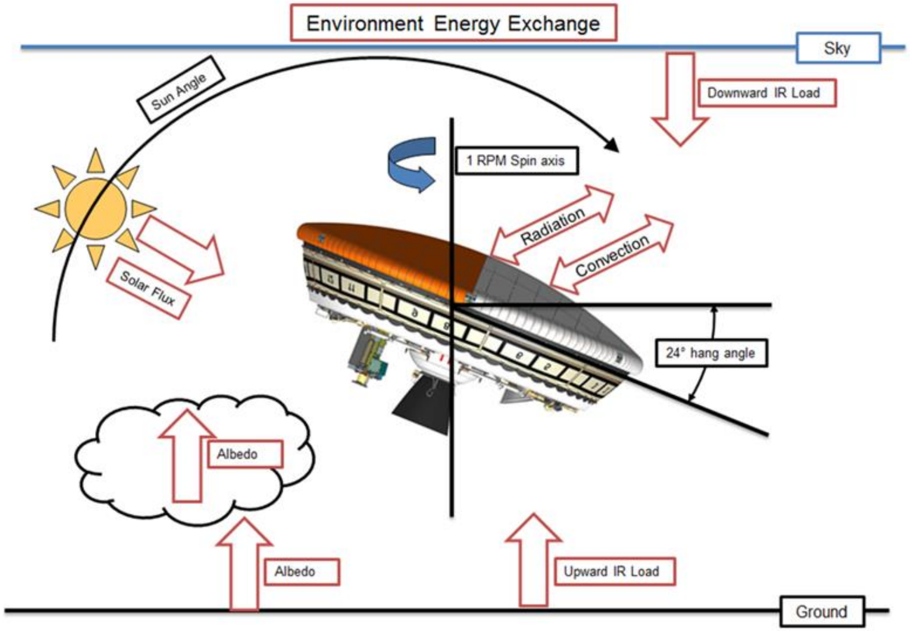


The LDSD Thermal Challenge:

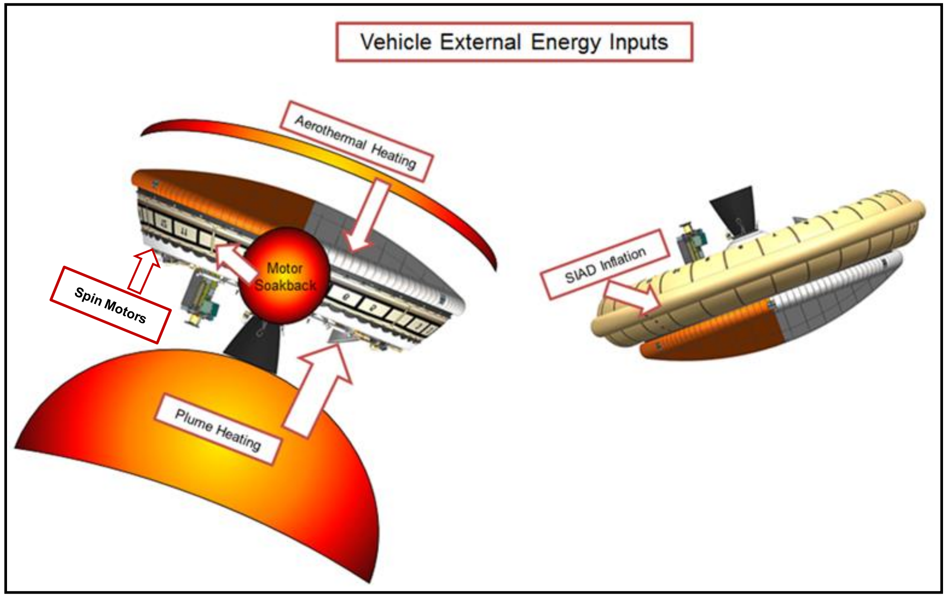
- How should one go about thermally analyzing/designing a high altitude balloon mission for an all composite vehicle that needs to fly the following?
  - high powered avionics
  - a 3rd stage Star-48 rocket motor that's to be ignited at only 120,000 ft altitude!
  - Fighter jet ejection seat thrusters used as spin up and spin down motors
  - cameras that are right next to the main motor rocket nozzle and plume
  - a brand new SIAD that generates its own heating during inflation and can also experience plume impacts from nearby spin motors
- Oh yeah by the way – there are no funds for system level TVAC testing, insufficient funds to implement previously qualified Space Shuttle TPS, ***AND*** no one knows exactly what the heat loads are for this mission!

Part 2
LDSD Thermal Analysis

Conduction, Convection, and Radiation are all relevant!

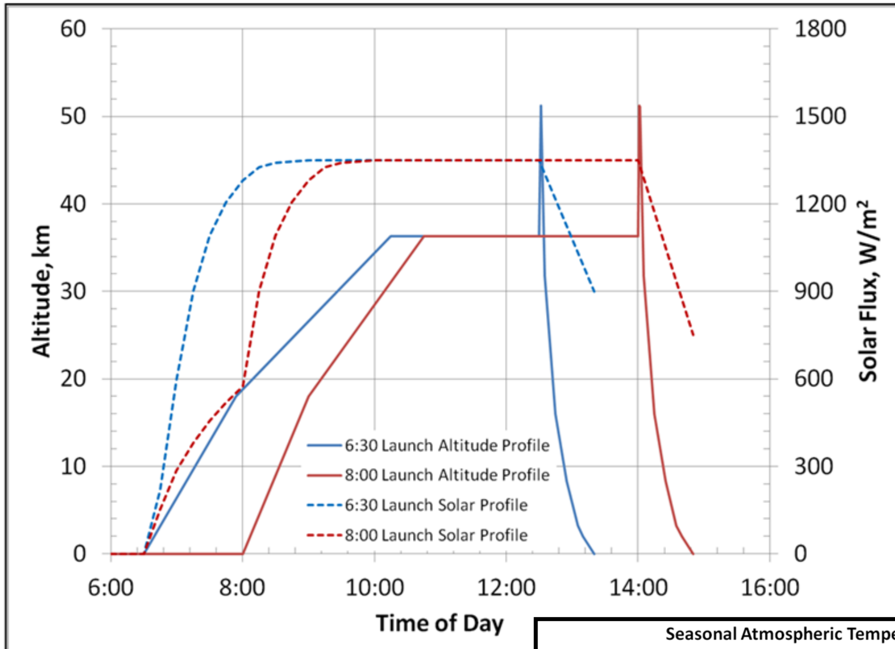


Ascent/Float Configuration

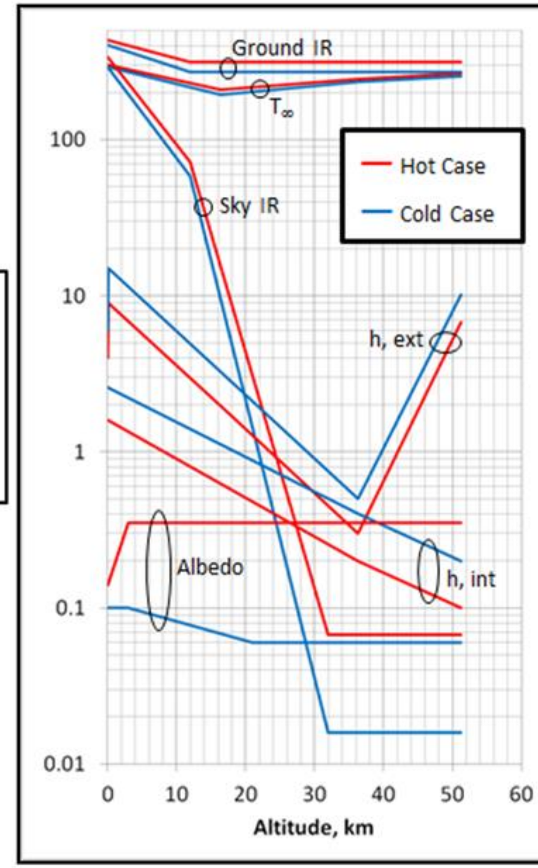


Powered Flight/Test Configuration

Altitude and Direct Solar Flux vs. Time

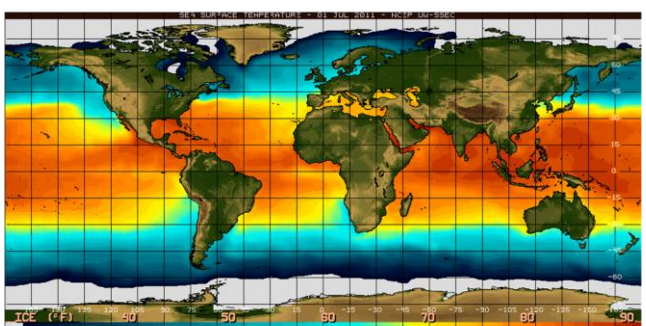


Vertical Axis Units:
Ground IR: W/m²
Sky IR: W/m²
T_∞: K
h, ext, int: W/m²K
Albedo: none



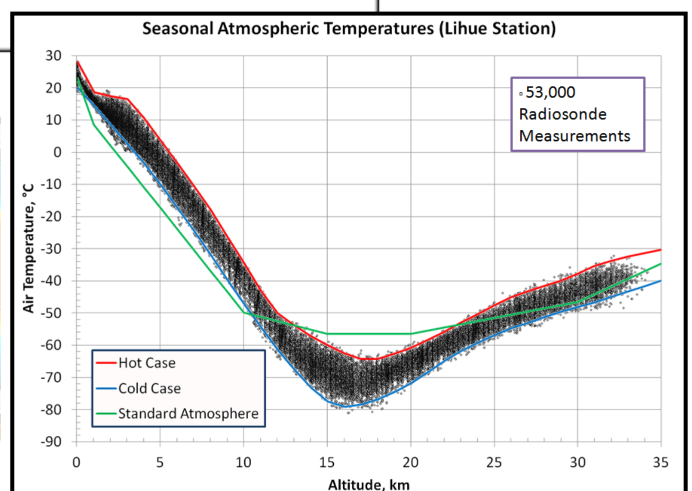
Sky Temperature: CSBF Analysis (Blackball Temperature during ascent)

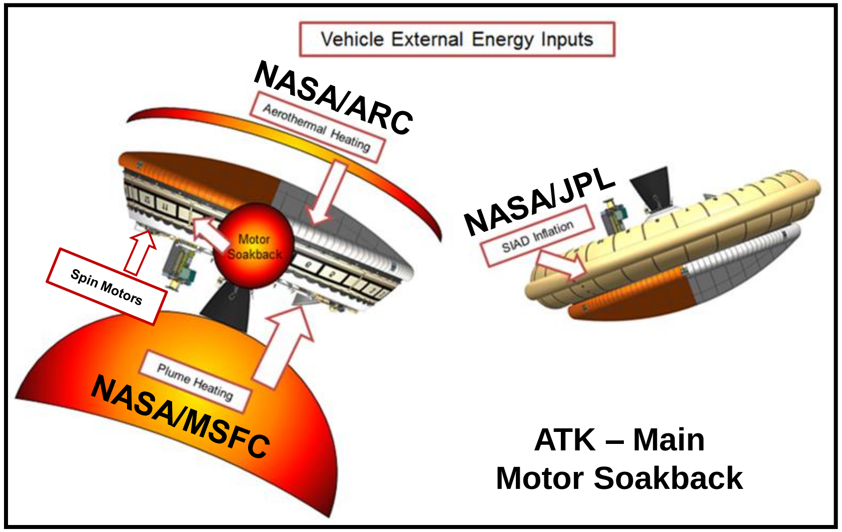
Global Sea Surface Temperature July 1, 2011



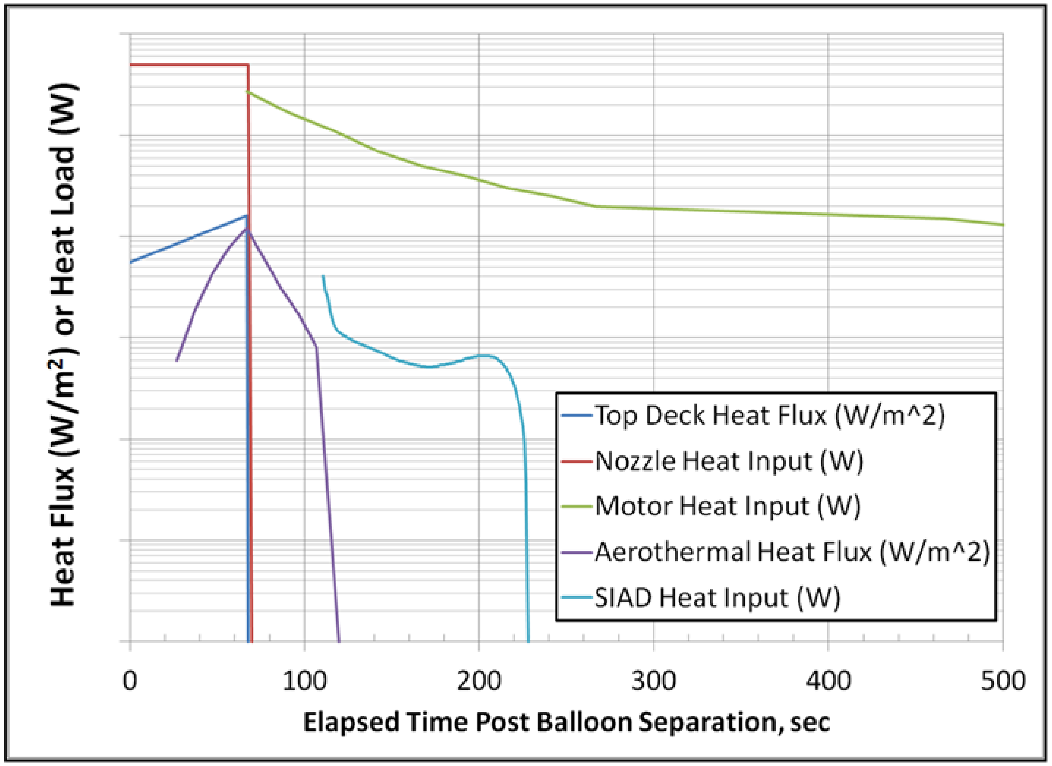
Space Science and Engineering Center, University of Wisconsin-Madison

21 to 27°C



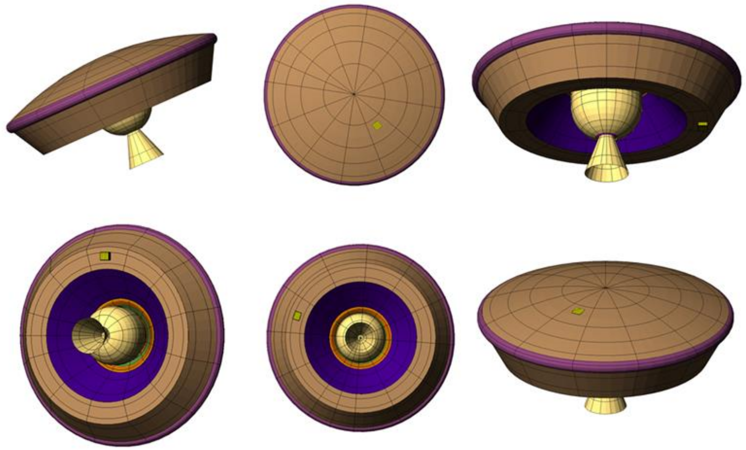


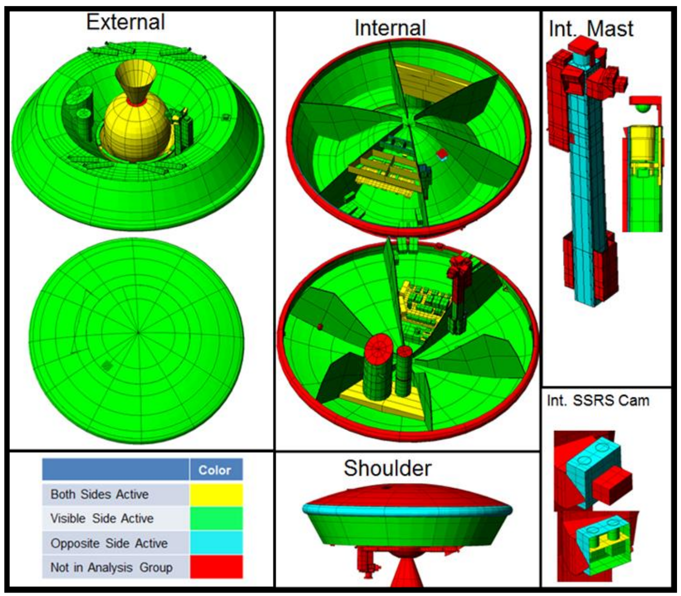
During Powered Flight & Test Phases



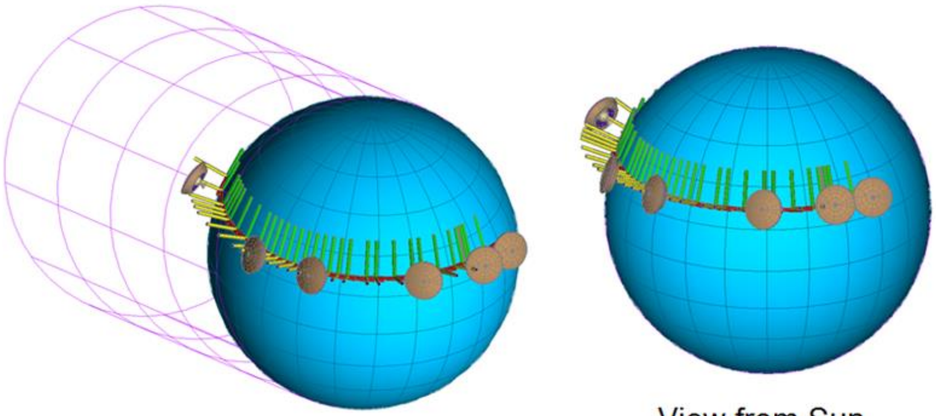
SFDT Vehicle Thermal Model

Thermal Desktop® Model of SFDT Vehicle

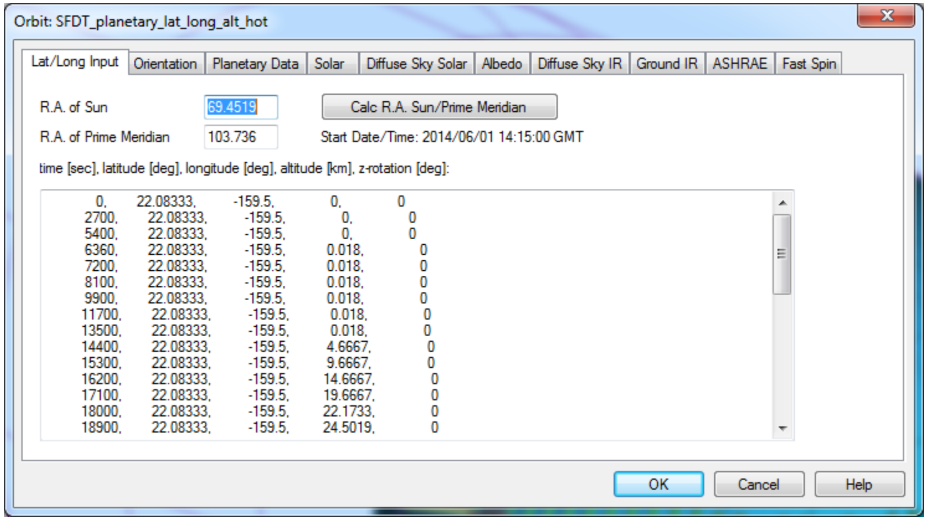




Longitude, Latitude, and Altitude Trajectory Positions



View from Sun



SFDT Vehicle Bounding Mission Cases

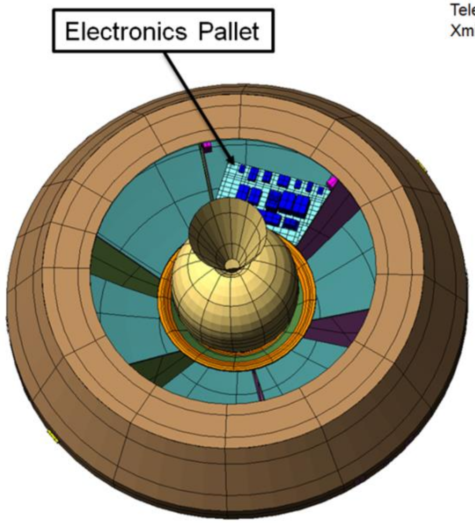
Definitions for Bounding Thermal Analysis

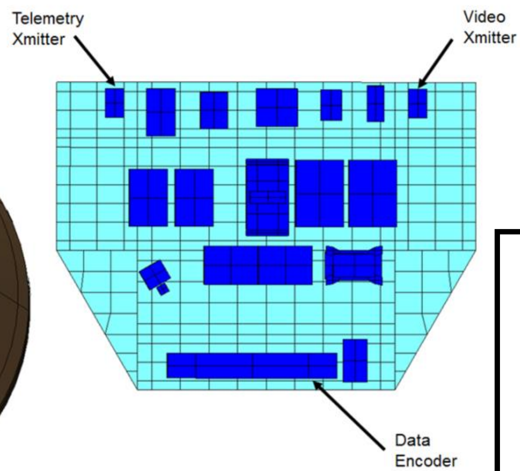
Worst Case Cold (WCC):	Worst Case Hot (WCH):

– longest ascent: 3.75 hr
– shortest float: 2.25 hr
– 6:30 AM launch
– cold boundary conditions
  – Sky Temperature
  – Ground Temperature
  – Ambient Air Temperature
  – Internal/External Convection
  – Solar/albedo
– CBE power
– CBE mass
	– shortest ascent: 2.75 hr
	– longest float: 3.25 hr
	– 8:00 AM launch
	– hot boundary conditions
	  – Sky Temperature
	  – Ground Temperature
	  – Ambient Air Temperature
	  – Internal/External Convection
	  – Solar/albedo
	– PBE power
	– CBE mass

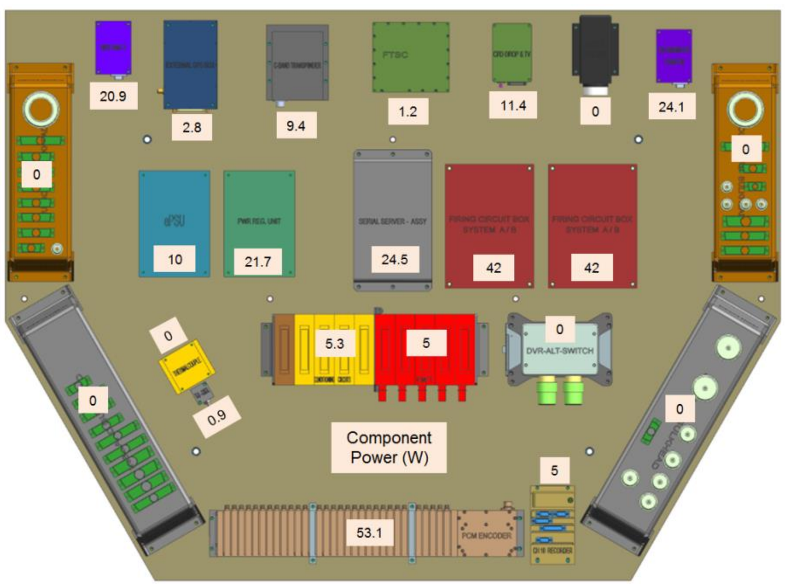
WCH Mission Timeline (8AM Launch)

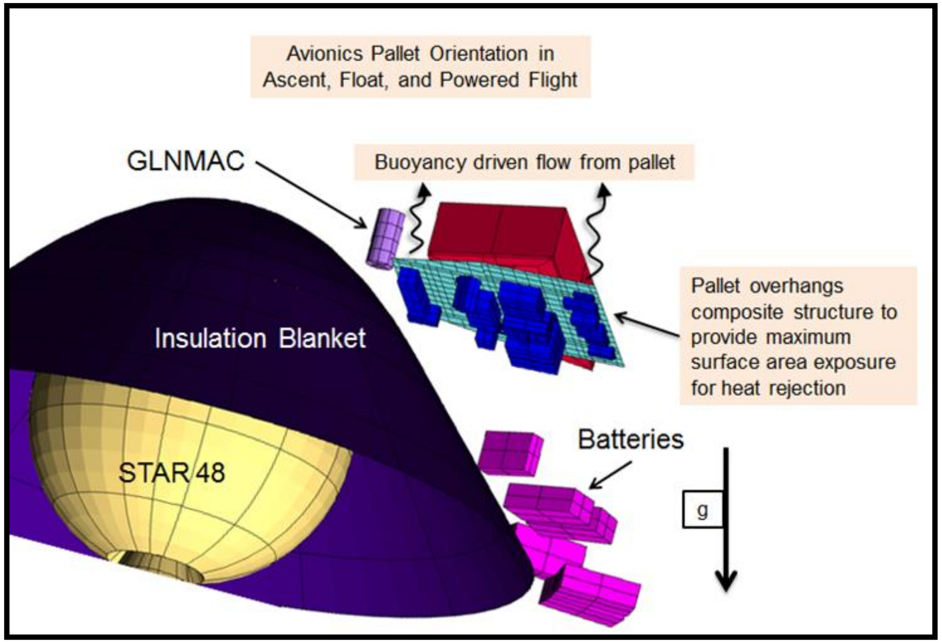
Mission Phase	Mission Event	Local Time HH:MM:SS	Elapsed Time Sec
Ground Operations	Pre-Lift Checkout, Power ON	4:15:00	0
	Pre-Lift Checkout, Power OFF	5:00:00	2700
	Vehicle Transfer	5:01:00	2760
	Post-Lift Checkout Power ON	6:00:00	6300
	Post-Lift Checkout Power OFF	6:30:00	8100
	Balloon Inflation	6:31:00	8160
	Pre-Launch Power ON	7:30:00	11700
Ascent	Launch	8:00:00	13500
Float	Float Start	10:45:00	23400
	Pre-Release Power ON 1	10:46:00	23460
	Power Down and Hold 1	11:31:00	26160
	Pre-Release Power ON 2	12:01:00	27960
	Power Down and Hold 2	12:46:00	30660
	Pre-Release Power ON 3	13:16:00	32460
	Release	14:01:00	35160
Powered Flight	Spin Up Motor Burn	14:01:00	35160
	Main Motor Burn	14:01:01	35162
	Spin Down Motor Burn	14:02:13	35233
Test	SIAD Deployment	14:02:52	35272
	PDD Deployment	14:04:29	35369
	SSRS Deployment	14:04:43	35383
Recovery	Splashdown	14:51:35	38195

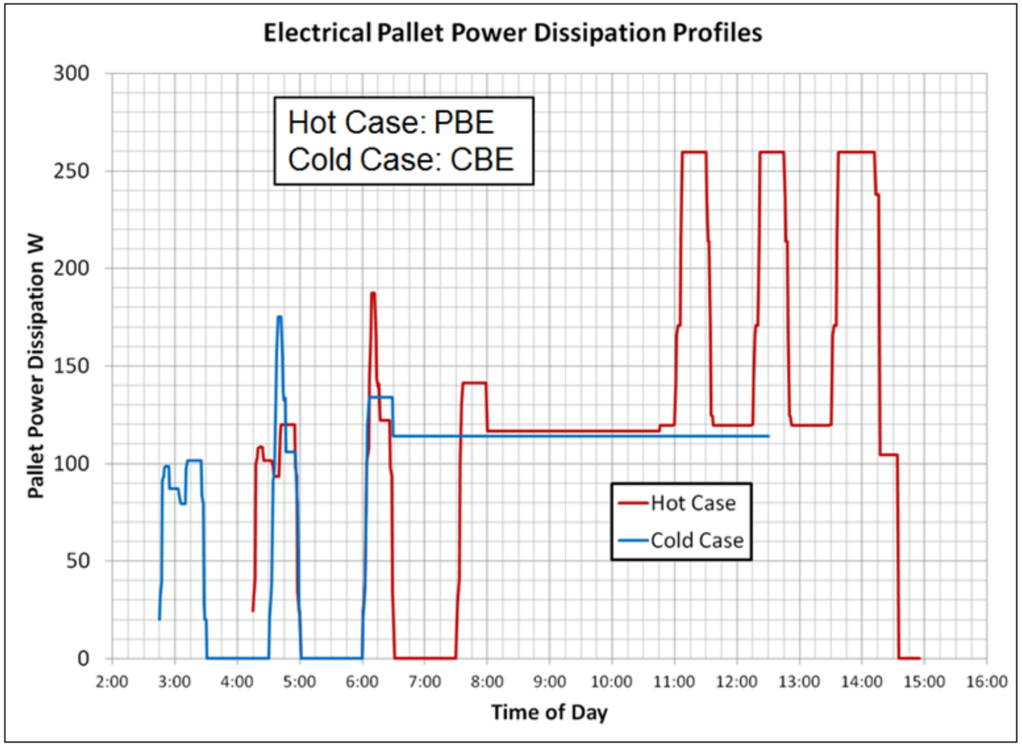




Optimized component layout was necessary to meet thermal requirements







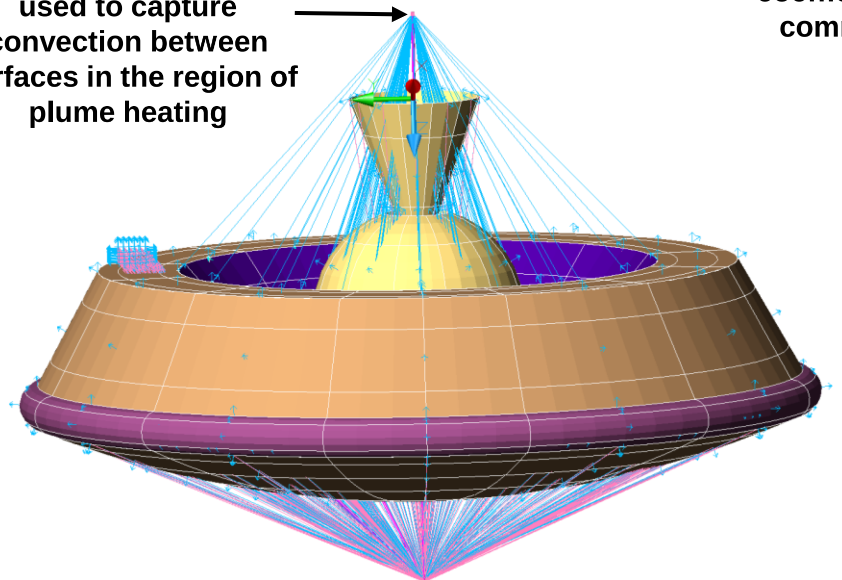
Pallet Components Temperature Requirements

SFDT Hardware Thermal Submodel Name	Temperature Requirements, C Allowable Flight Operational min	max	Nonoperational min	max
Wallops On-Pallet Components				
ATTSW	-39	51	-39	51
CBNDXPNDR	-25	61	-47	75
COLDJNCTN	-40	130	-40	130
CONDCIRC	-25	65	-25	65
CONDCIRC	-14	51	-44	75
CRD1	-39	65	-47	75
CRD2	-39	65	-47	75
EPSU	-25	65	-25	80
FIRINGA	-25	65	-25	65
FIRINGB	-25	65	-25	65
FTSC	-14	51	-24	61
GPSRCVR	-20	55	-25	65
LEDEX	-40	60	-40	60
PWRREG	-20	65	-25	80
RMFT	-14	51	-44	75
SERSRVR1/SERSRVR2	-25	60	-25	65
SERSW	-25	55	-25	65
TRIAX	-40	90	-40	90
TTCENCODR	-40	85	-40	85
TTCRECORD	-20	65	-40	65
VIDCOMBNR	-5	60	-5	60
XMRTVID	-40	85	-40	85
XMTRTM	-40	85	-40	85

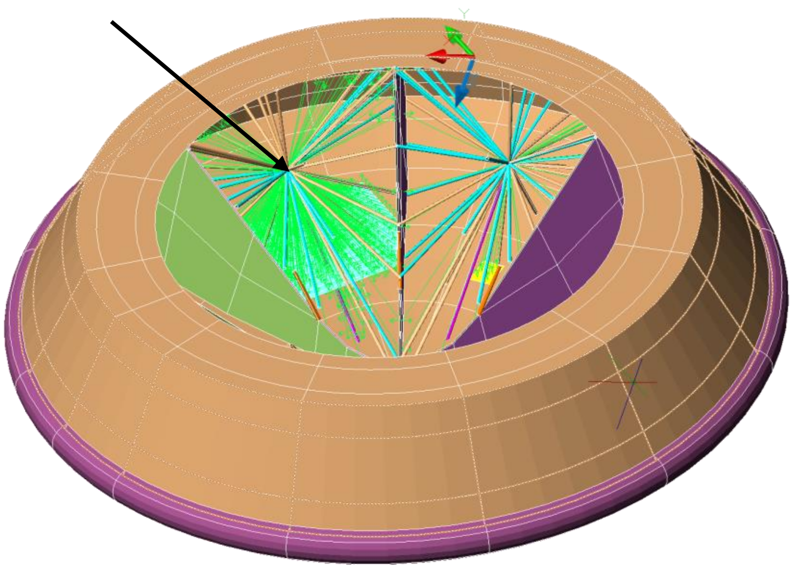
External convection modeled for all surfaces

Internal convection modeled for 2-bays

An arithmetic node is used to capture convection between surfaces in the region of plume heating

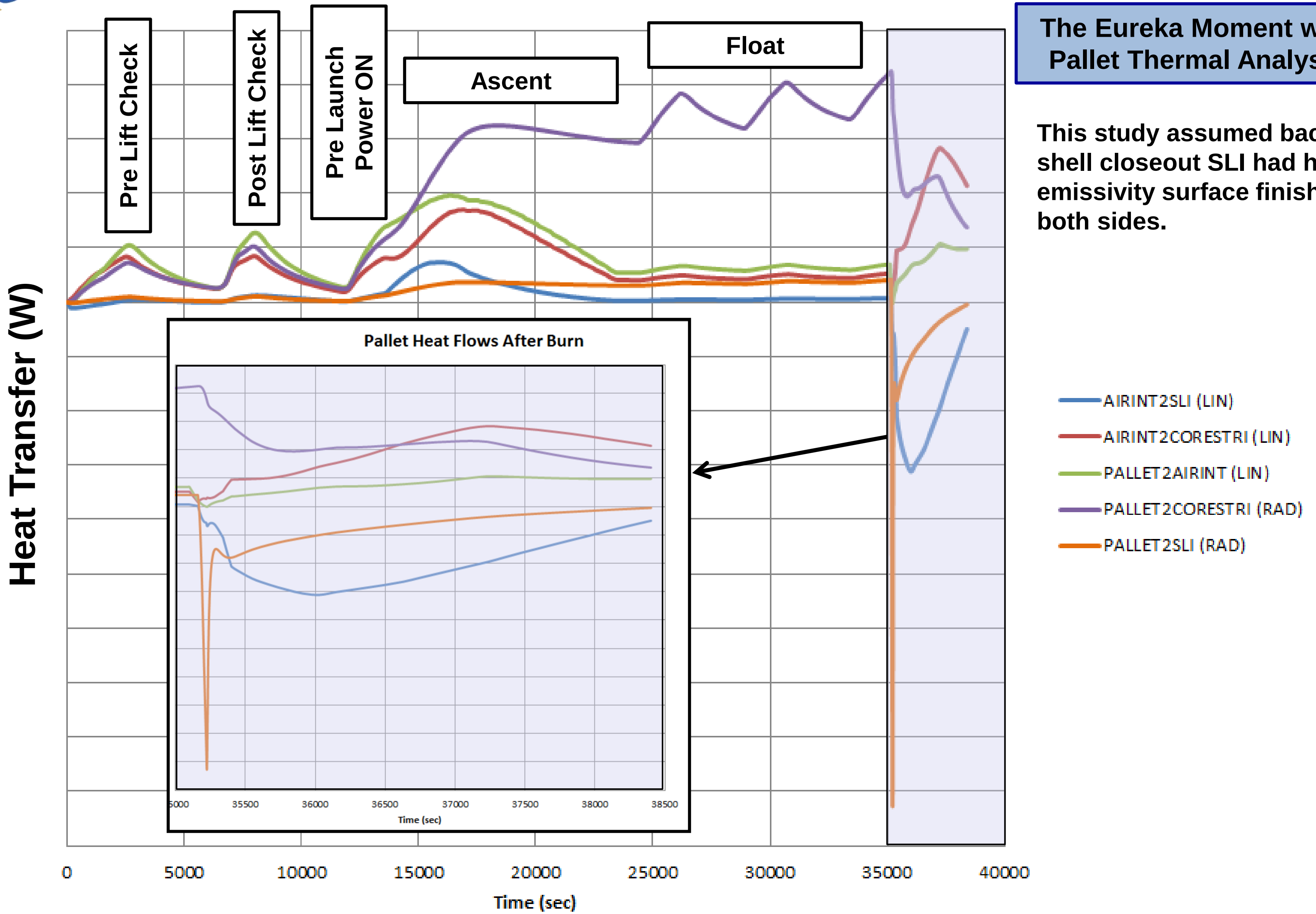


For each of two bays, conductors with time-dependent heat transfer coefficients tie surfaces to a common arithmetic node



Conductors with time-dependent heat transfer coefficients tie surfaces to a boundary node of time-dependent air temperatures

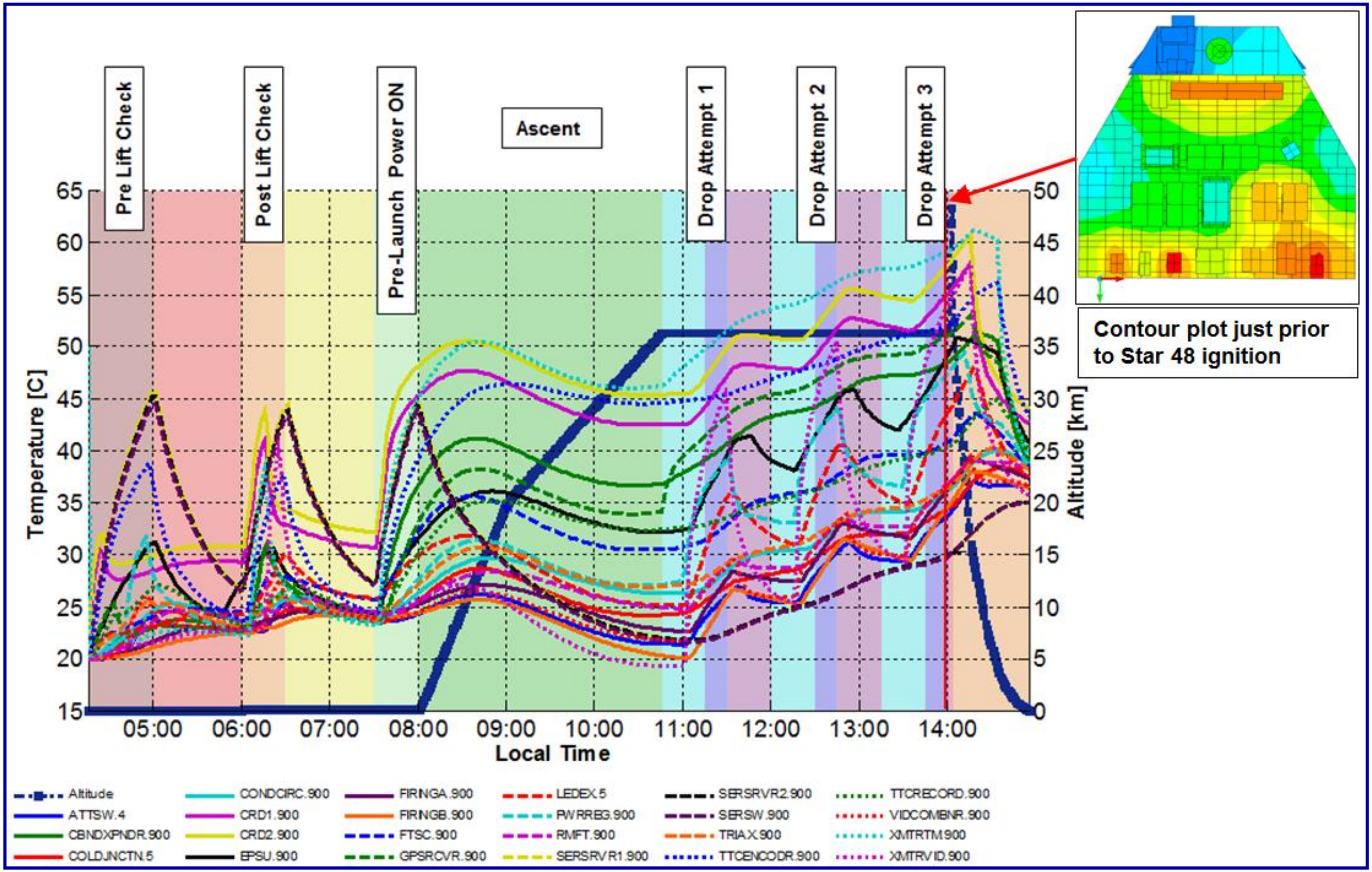
Thermal Analysis of the Electronics Pallet (4/5)



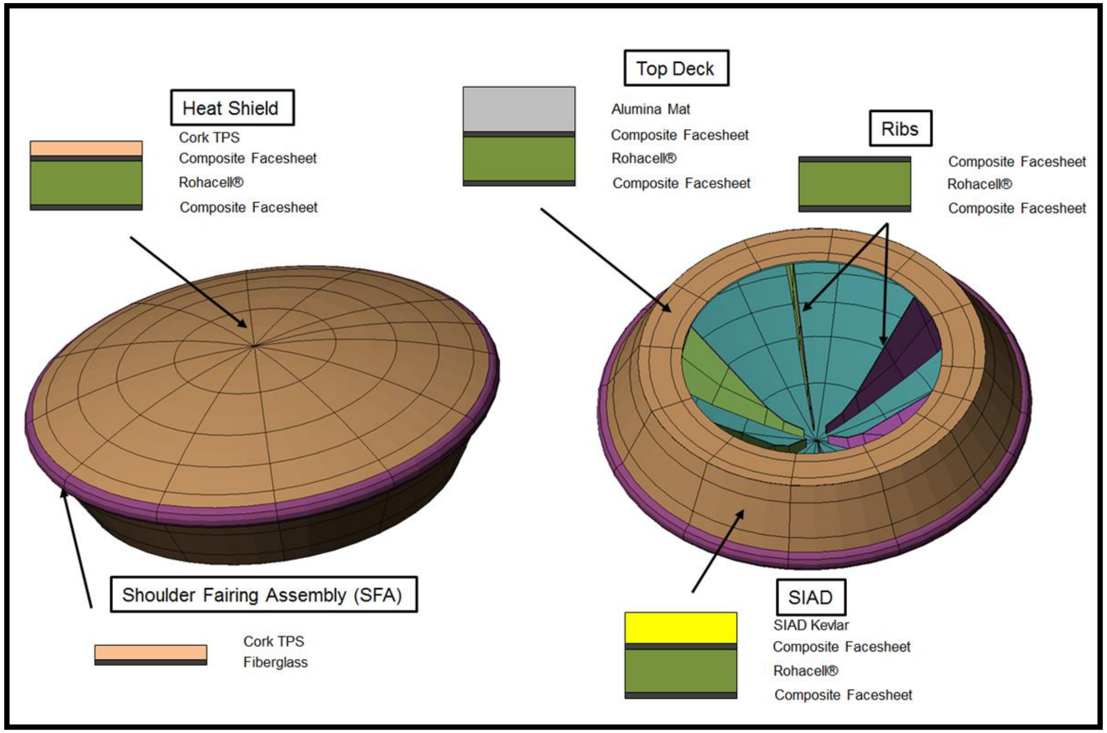
The Eureka Moment with Pallet Thermal Analysis

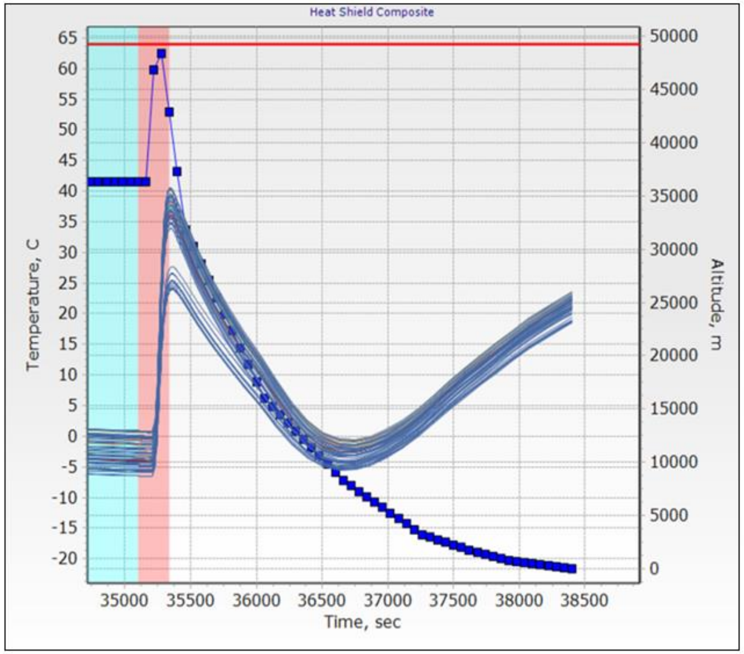
This study assumed back shell closeout SLI had high emissivity surface finish on both sides.

Thermal Analysis of the Electronics Pallet (5/5)



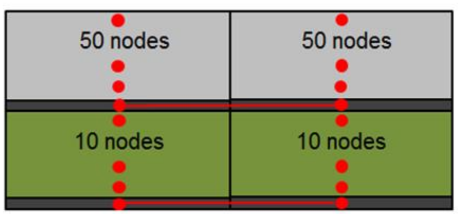
Thermal Analysis of the Core Structure Assembly



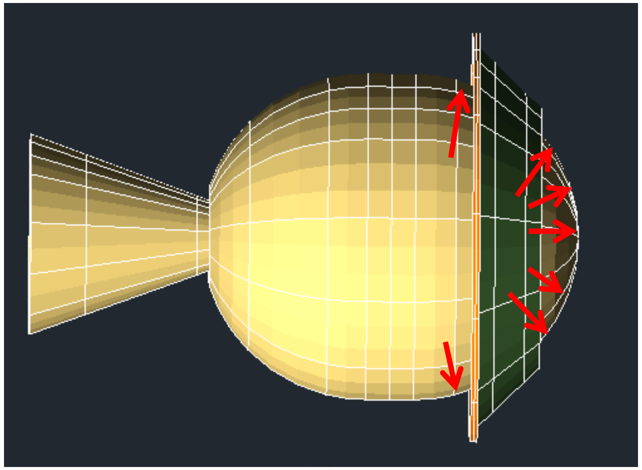


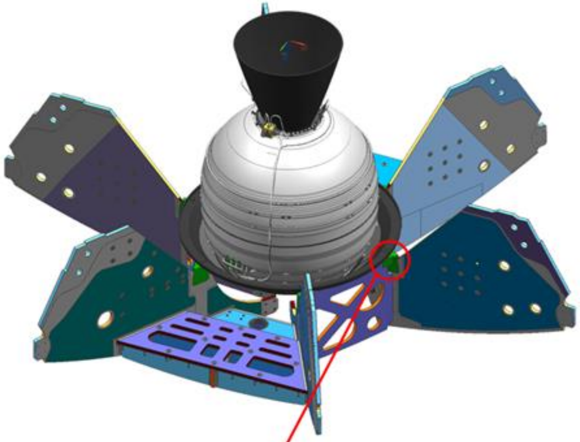
Appropriate nodal fidelity is critical through thickness of low thermal diffusivity material

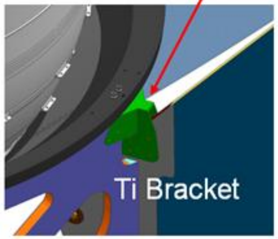
Exterior Composite Facesheet Underneath Heat Shield



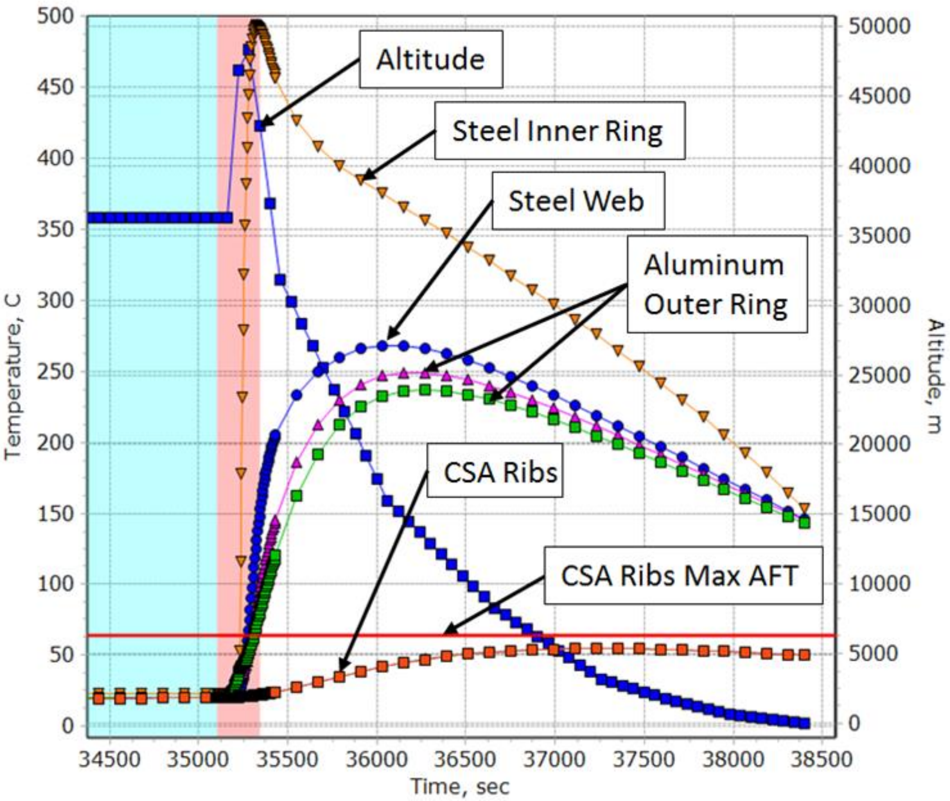
Alumina Mat, Cork, or SIAD
Composite Facesheet
Rohacell®
Composite Facesheet





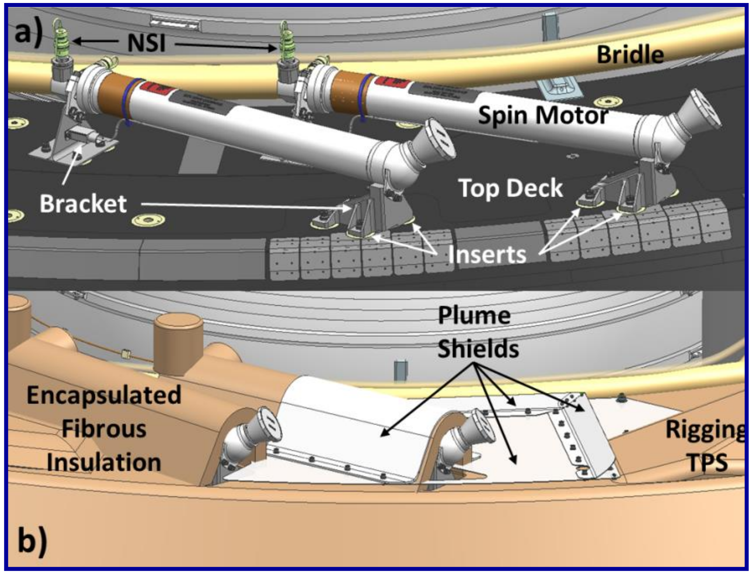


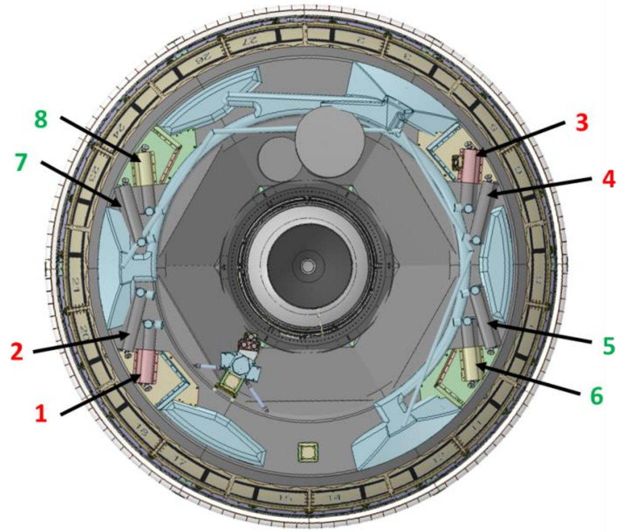
Slag Conservative Bounding Case: Soakback energy concentrated in forward dome - internal radiation ON

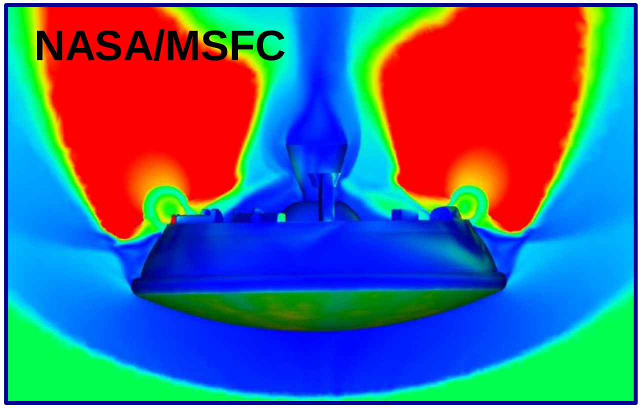


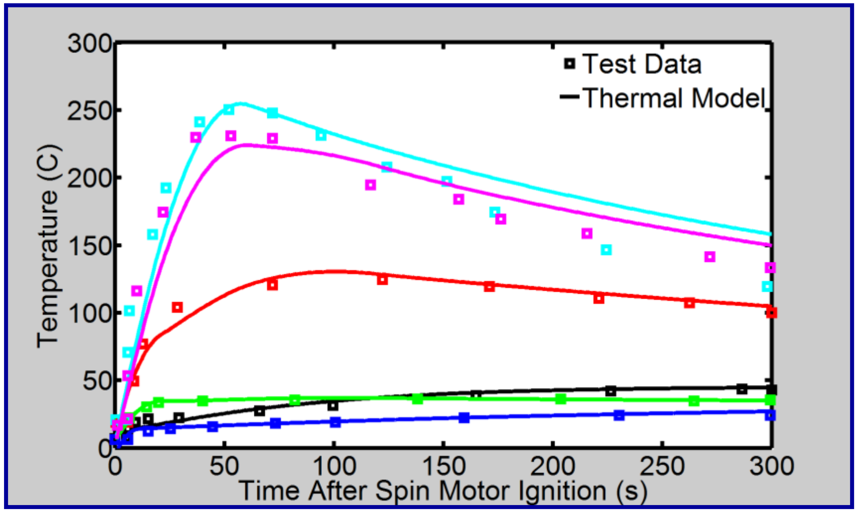
Thermal Analysis of Spin Motors

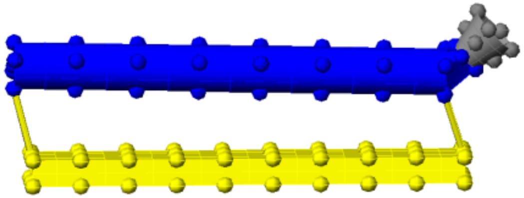
a) without TPS b) with TPS











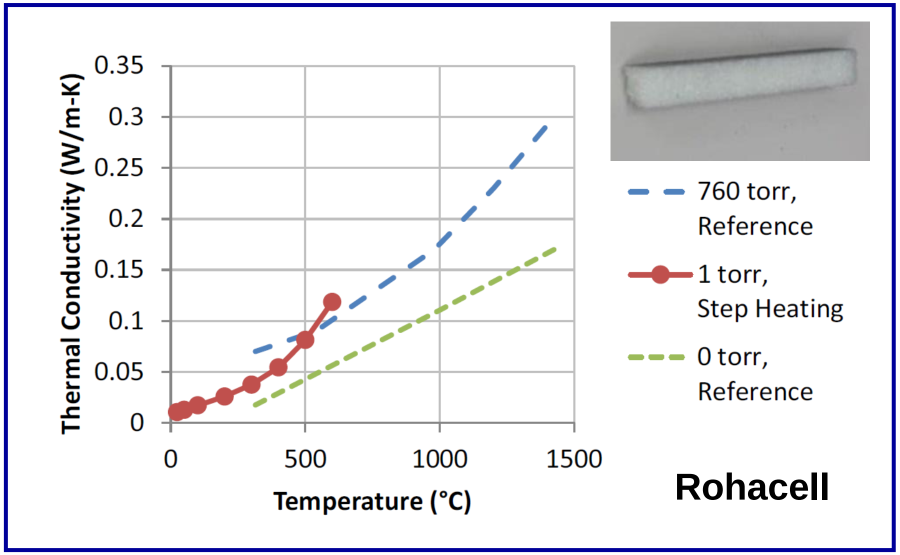
Thermal Material Property Measurements

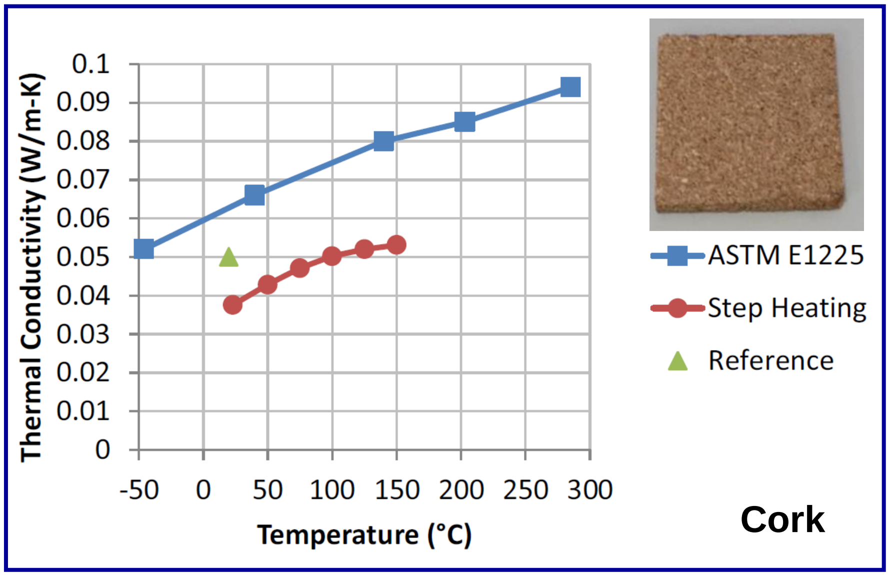
Material	Thermal Emissivity	Solar Absorptivity
Carbon Composite	0.83	0.91
Carbon Composite, Sanded	0.83	0.91
Cork, 1 Coat of White Zynolyte® HiTemp Paint	0.88	0.34
Cork, 2 Coats of White Zynolyte® HiTemp Paint	0.87	0.27
Cork, 3 Coats of White Zynolyte® HiTemp Paint	0.88	0.22
Cork, 4 Coats of White Zynolyte® HiTemp Paint	0.90	0.22
Polyken® 223 White Duct Tape on Bare Aluminum	0.86	0.36
Polyken® 223 White Duct Tape on Carbon Composite	0.89	0.46
Polyken® 223 White Duct Tape, 4 Layers	0.88	0.33

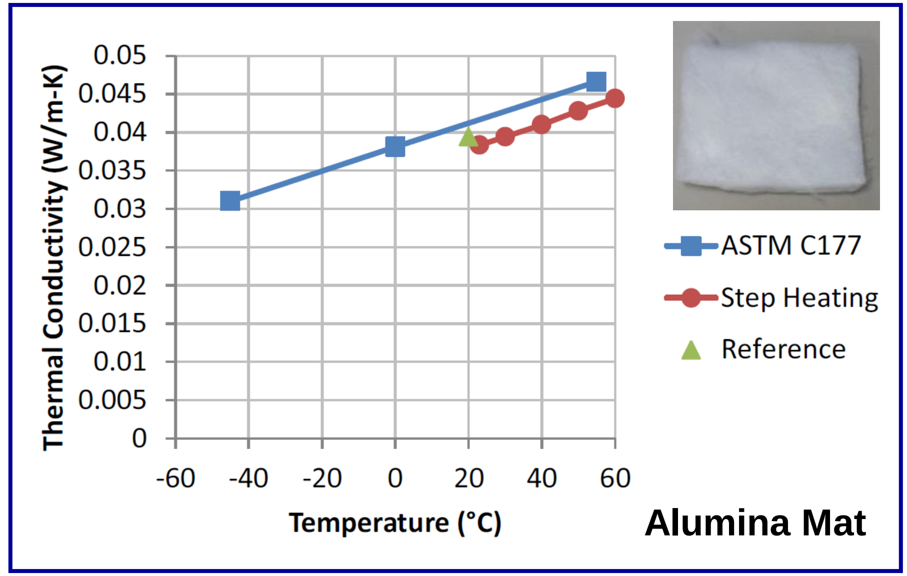
Same

Decreasing Absorptivity

Duct Tape Partially Transparent

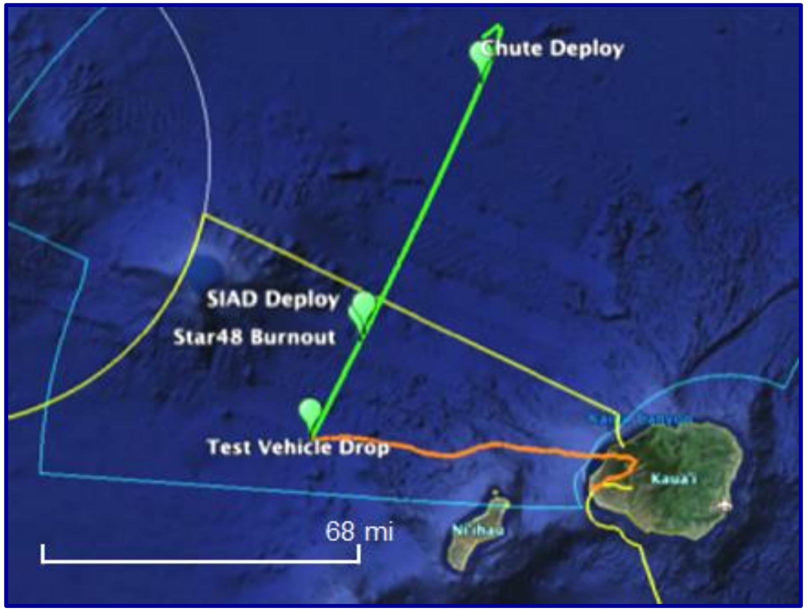






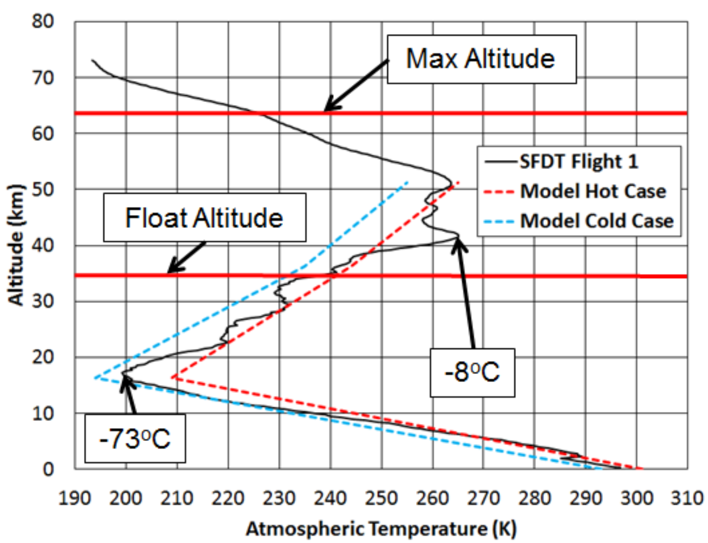
Part 3
SFDT-1 Flight Test Results

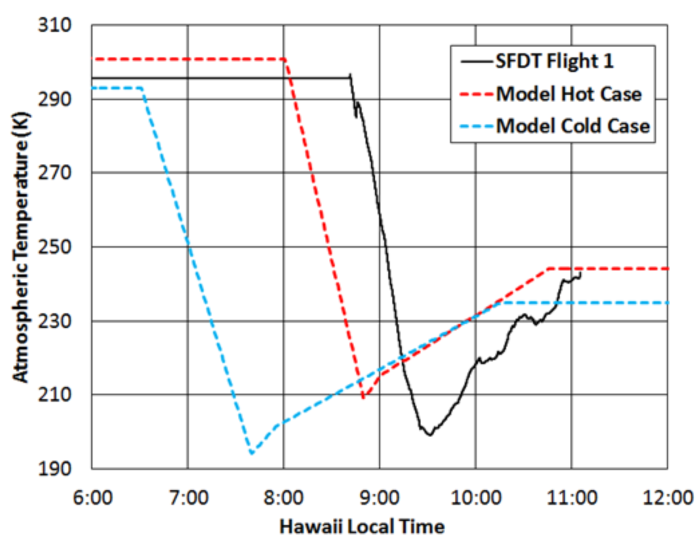
Day of Test Thermal Environment, Trajectory, & Timeline



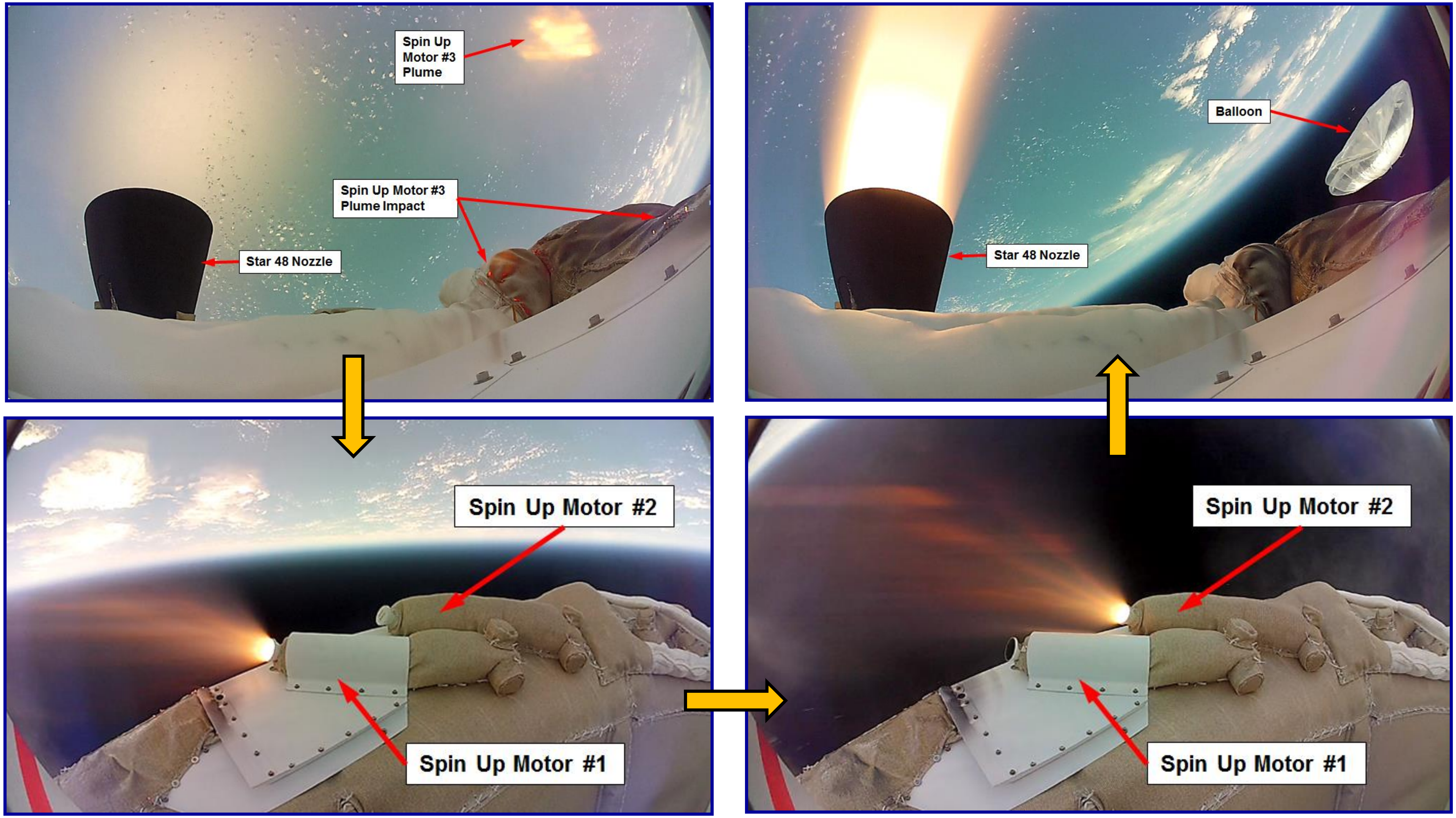
Critical Event	UTC	HST
Pre-Lift Check Begins	12:02:00	2:02:00
Pre-Lift Check Complete	12:32:00	2:32:00
Post Lift Check Begins	15:47:00	5:47:00
Post-Lift Check Complete	16:05:00	6:05:00
Pre-Launch Power ON	18:00:00	8:00:00
Balloon Launch	18:40:51	8:40:51
Balloon Rotator ON	20:05:53	10:05:53
Balloon Rotator Set	20:18:59	10:18:59
TV Block 1 Power ON	20:25:10	10:25:10
TV Block 2 Power ON	20:30:07	10:30:07
TV Block 3 Power ON	20:35:37	10:35:37
TV Block 4 Power ON	20:50:14	10:50:14
Float Achieved	21:02:47	11:02:47
GLNMAC Init	21:03:01	11:03:01
Drop	21:05:00	11:05:00
Spin Up	21:05:00	11:05:00
Star 48 Ignition	21:05:02	11:05:02
Star 48 Burnout Detected	21:06:11	11:06:11
Spin Down	21:06:12	11:06:12
SIAD Deploy	21:06:22	11:06:22
PDD Mortar Fire	21:07:41	11:07:41
SSDS Full Inflation	21:07:49	11:07:49
FIR Cable Cut	21:10:53	11:10:53
EPSU Altitude Switch Closure	21:19:20	11:19:20
All Buses Powered OFF	21:19:32	11:19:32

June 28, 2014

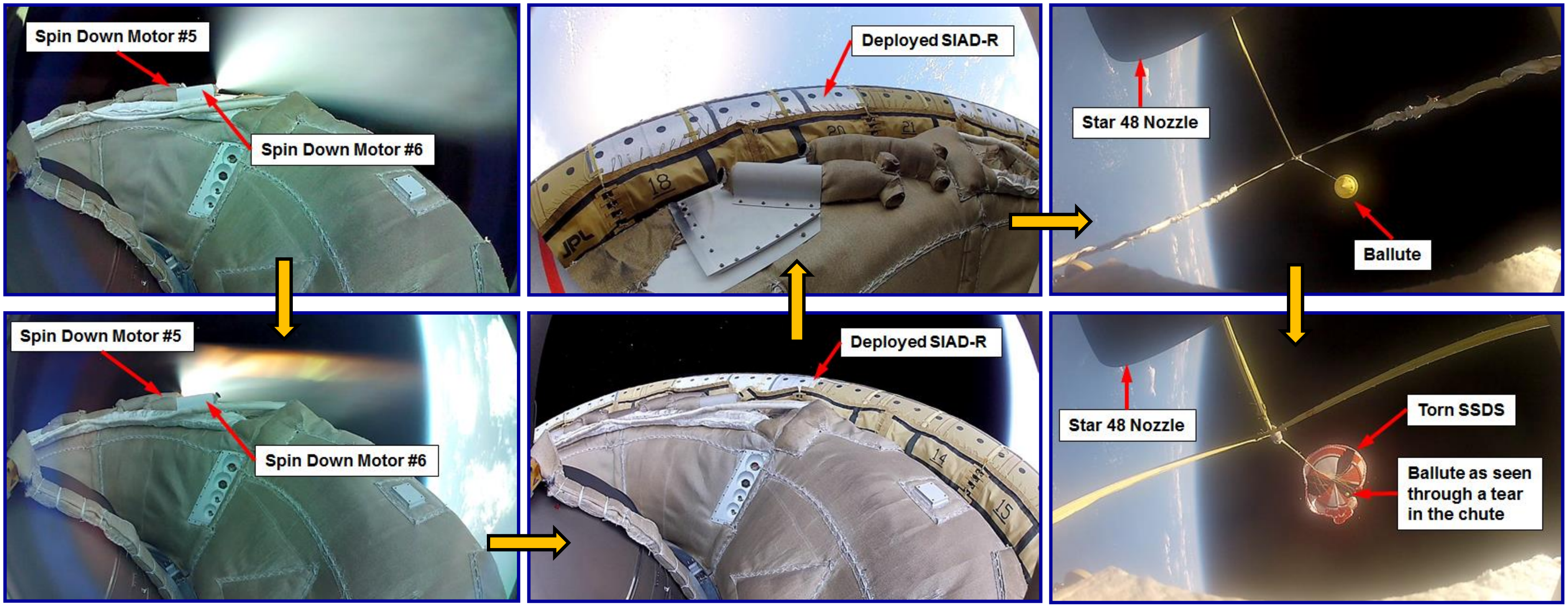




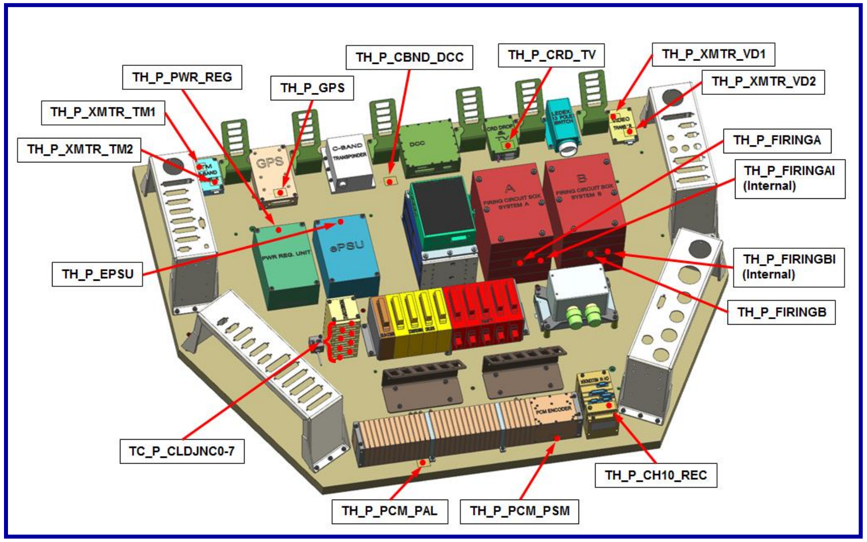
SFDT-1 Key Events (1/2)

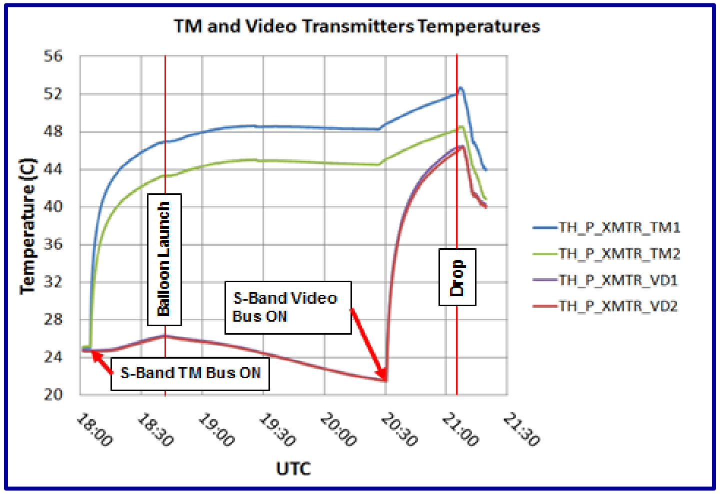


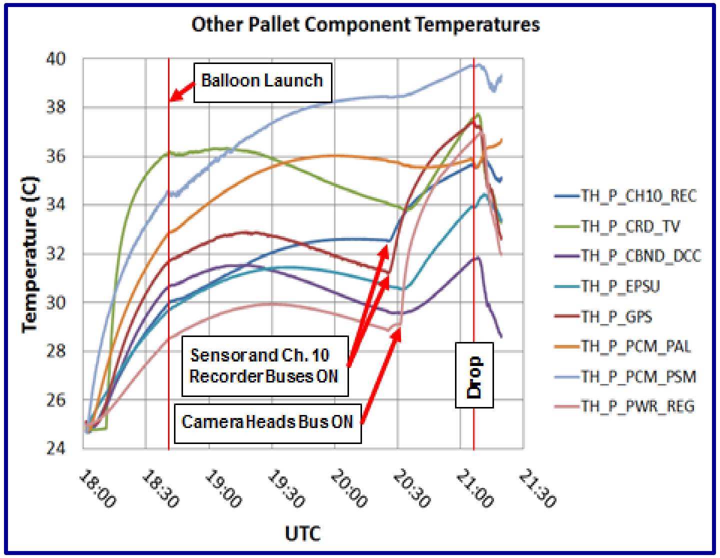
SFDT-1 Key Events (2/2)

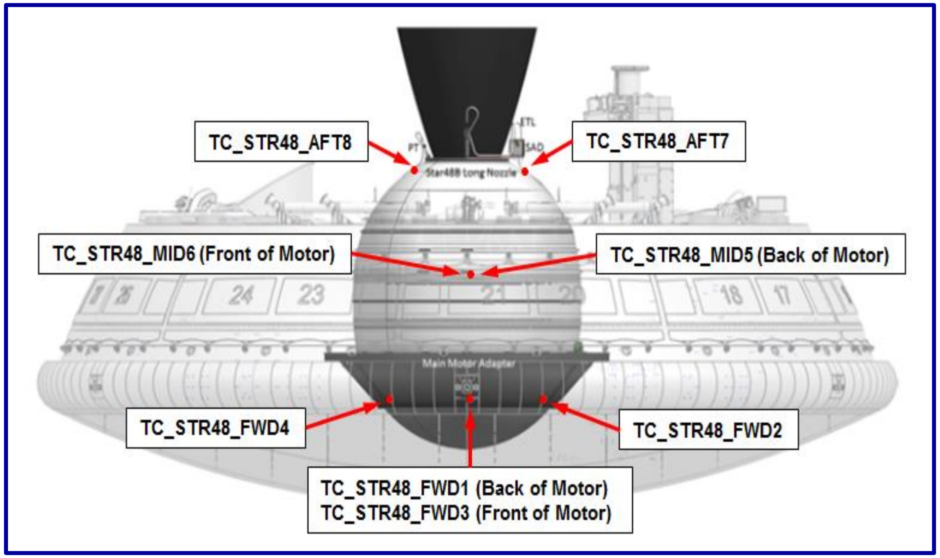


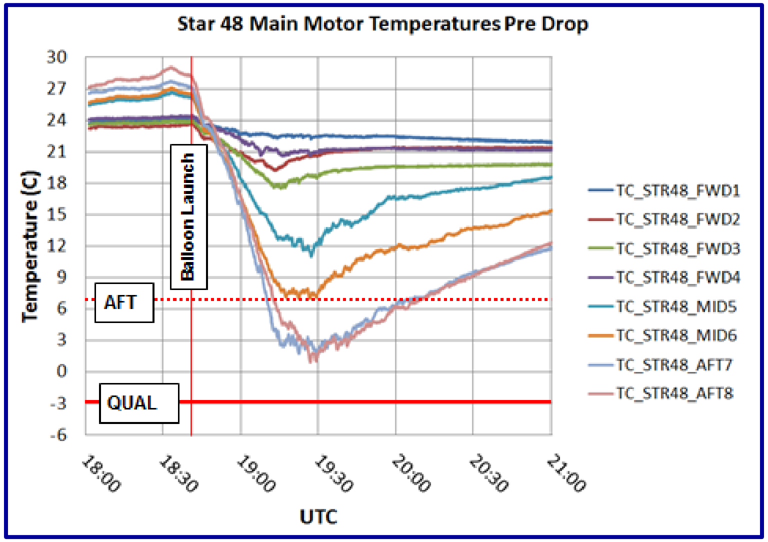
SFDT-1 Thermal Telemetry – Electronics Pallet

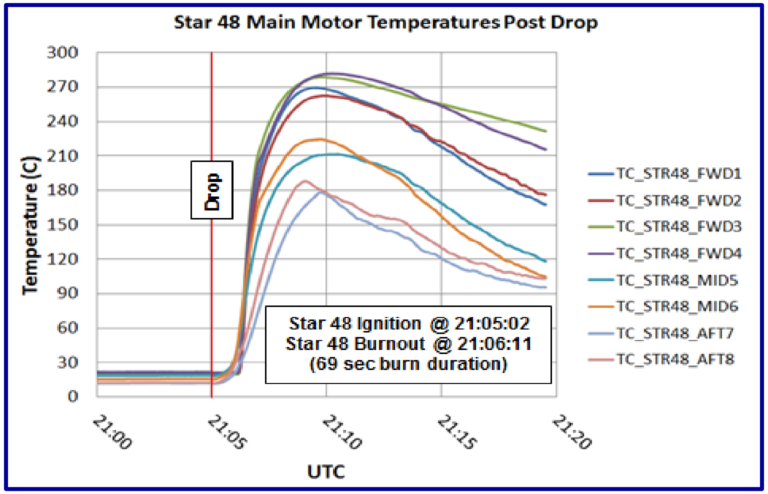






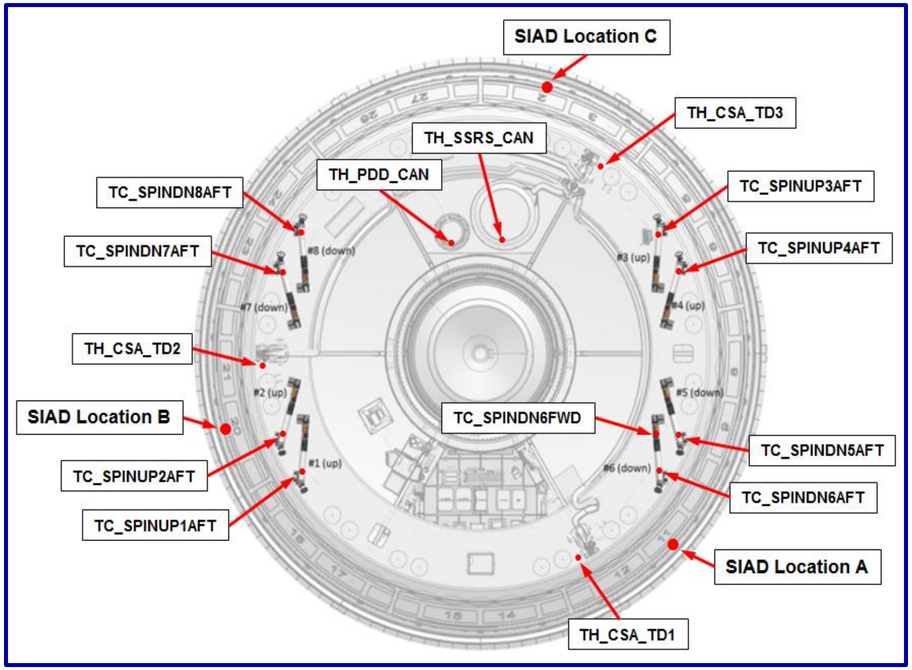


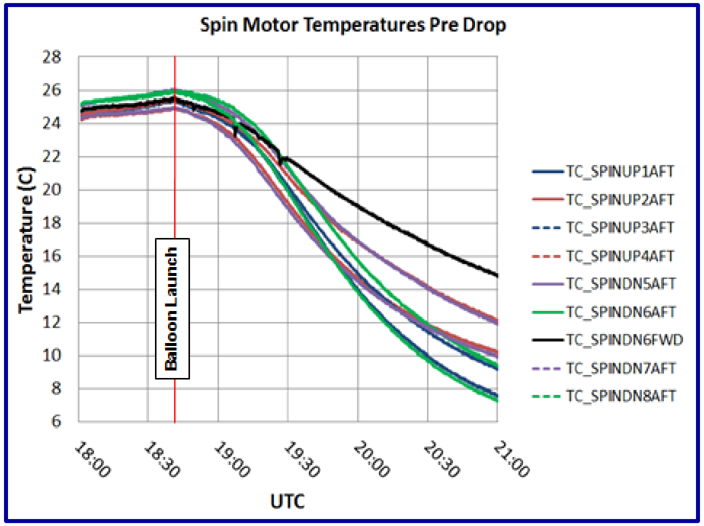


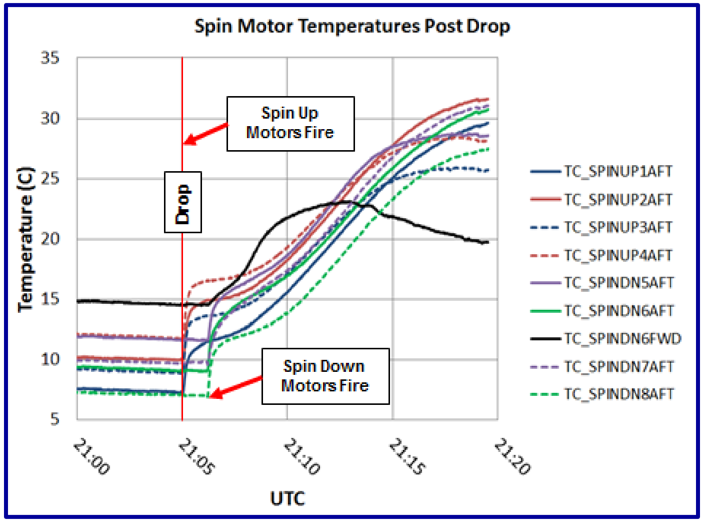


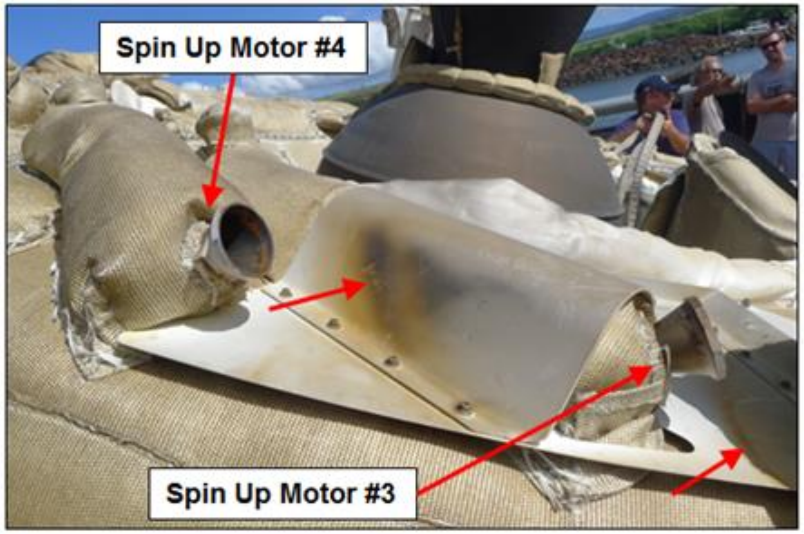
Only 1 AFT violation occurred briefly during the balloon ascent near the nozzle end of the Star 48.

SFDT-1 Thermal Telemetry – Spin Motors







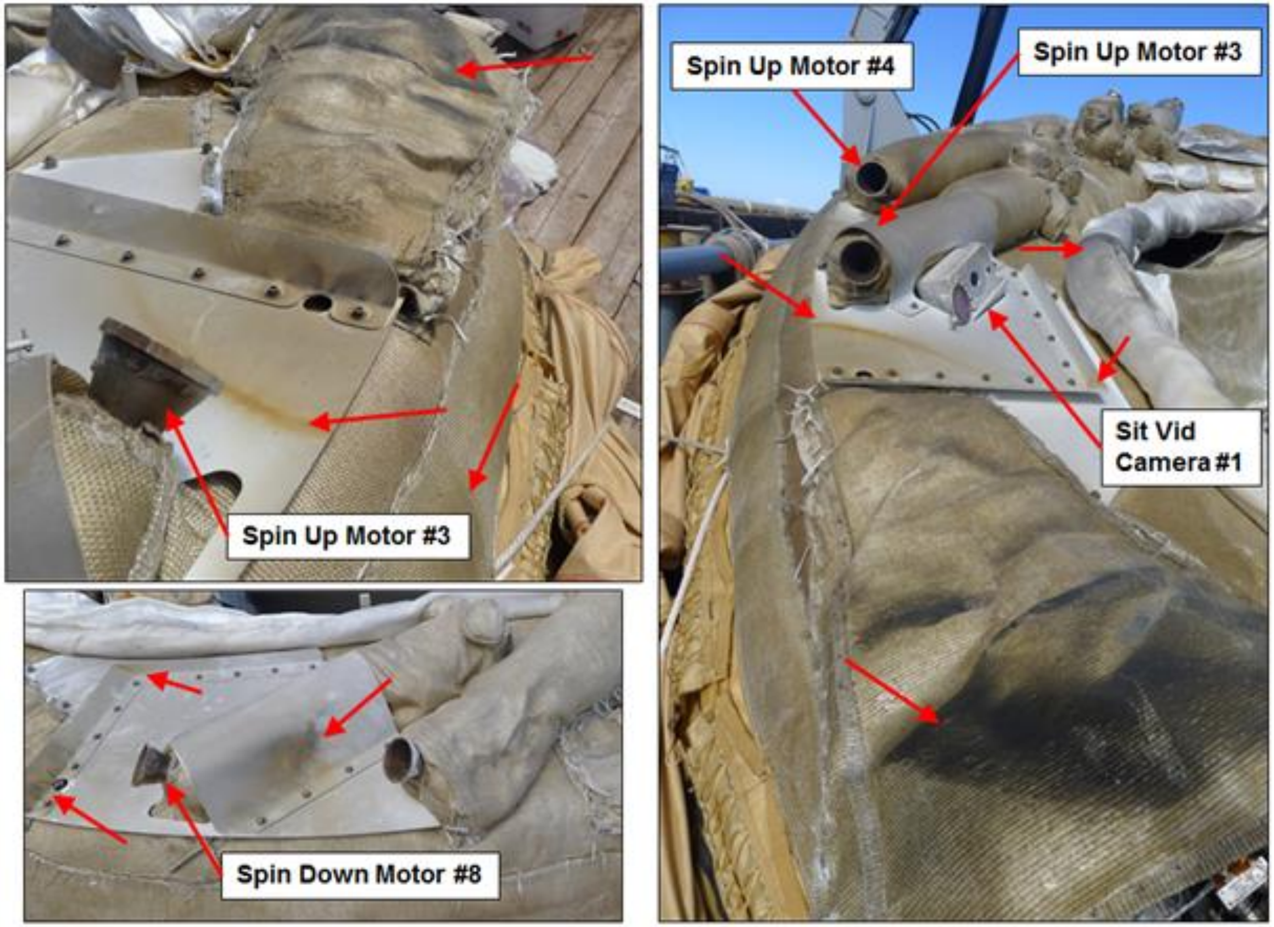


Spin Up Motor #4
Spin Up Motor #3

FIR

Missing paint on nozzle
Spin Up Motor #1

Post-Flight Visual Inspection of the Recovered TV (2/2)



Lessons Learned

- Thermal engineering and analysis was vital to the success of the LDSD Project!
- There was a desire to use many COTS parts to save costs; however, many were ***not designed to operate in a near vacuum environment*** and had to be repackaged to enable conduction/radiation cooling.
- For COTS parts, make sure there is adequate temperature margin reserved between a vendors advertised temperature range and the Allowable Flight Temperatures - recommend at least +/- 10°C qual margin.
- Material property measurements were invaluable – advertised data is often wrong.
  - Had to repaint part of our heat shield white after a handbook value for an orange paint alpha turned out to be much higher as confirmed by measurements.
- Transient heat flow analysis proved invaluable toward understanding how to best safeguard the pallet from the high heating events.

Conclusions

- The bounding thermal analysis methodology employed for the LDSD high altitude balloon mission worked well.
  - All components experienced temperatures within worst case predicts with the exception of the previously noted temporary violation near the nozzle end of the Star 48.
- 4 major thermal challenges in particular had to be conservatively estimated:
  - Star 48 main motor plume heating
  - Star 48 soakback heating
  - Spin motor plume heating
  - Spin motor soakback heating
- Thermal telemetry and post-flight visual inspection of the recovered TV from the first test flight confirmed that the SFDT vehicle thermal design was robust to the 4 major thermal challenges.
  - Temperatures for the electronics pallet, CSA, main motor, and spin motors remained quite benign.

Acknowledgements

LDSD Thermal Team

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- Sandria Gray
- Brenda Hernandez
- Eric Sunada
- Mark Duran
- Richard Frisbee

LDSD Mechanical Team

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- Kevin Burke
- John Luke Wolf
- Gabriela Molina
- Many Others

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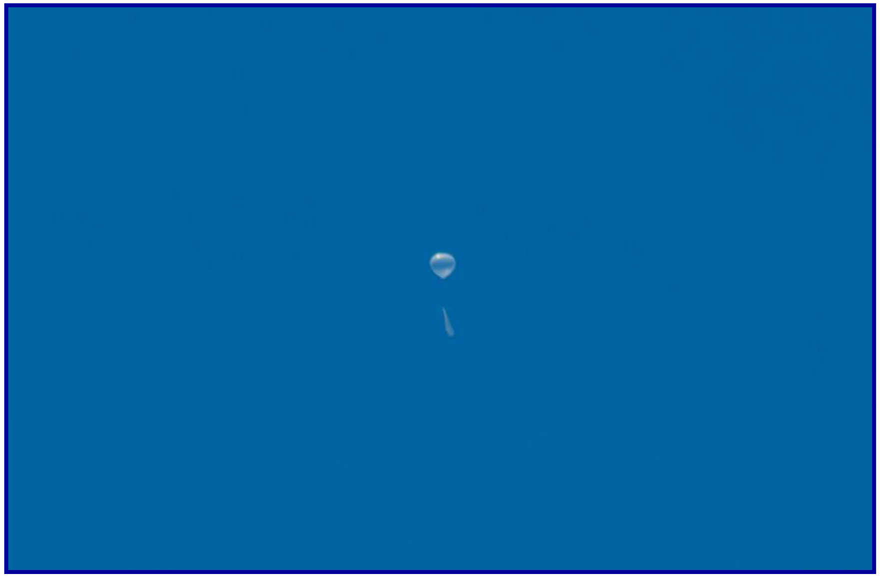
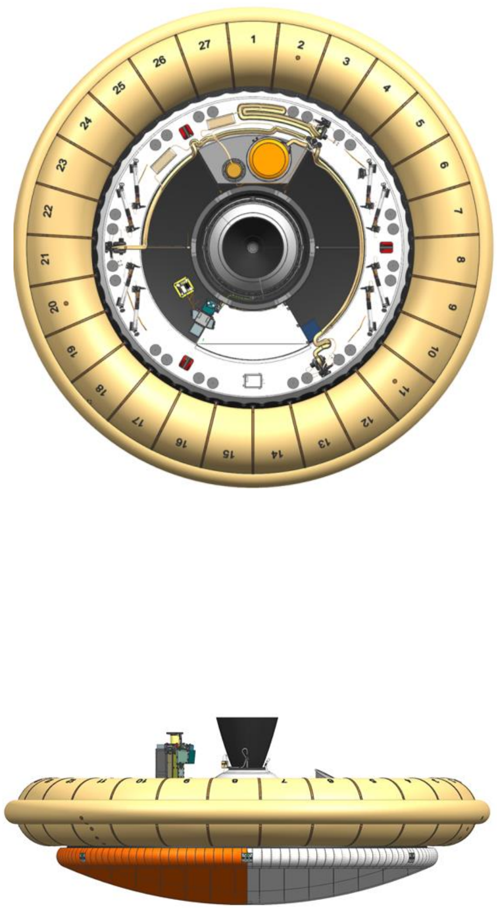
- [1] Clark, I., and Blood, E., "*Low Density Supersonic Decelerator (LDSD) Supersonic Flight Dynamics Test-1 (SFDT-1) Post –Test Report*," JPL Internal Document, D-81940, December 2014.
- [2] Mastropietro, A. J., Pauken, M., Sunada, E., and Gray, S., "*Thermal Design and Analysis of the Supersonic Flight Dynamics Test Vehicle for the Low Density Supersonic Decelerator Project*," AIAA-2013-3348, 43rd International Conference on Environmental Systems, Vail, CO, 2013.
- [3] Redmond, M., Mastropietro, A. J., Pauken, M., and Mobley, B., "*Passive Thermal Control for the Low Density Supersonic Decelerator (LDSD) Test Vehicle Spin Motors Sub-System*," ICES-2014-031, 44th International Conference on Environmental Systems, Tucson, AZ, 2014.
- [4] Mastropietro, A. J., Kempenaar, J., Redmond, M., Pauken, M., and Ancarrow, W., "*First Test Flight Thermal Performance of the Low Density Supersonic Decelerator (LDSD) Supersonic Flight Dynamics Test (SFDT) Vehicle*," ICES-2015-328 in 45th International Conference on Environmental Systems, Bellevue, WA, 2015.
- [5] Redmond, M., and Mastropietro, A. J., "*Thermophysical and Optical Properties of Materials Considered for use on the LDSD Test Vehicle*," ICES-2015-024, 45th International Conference on Environmental Systems, Bellevue, WA, 2015.

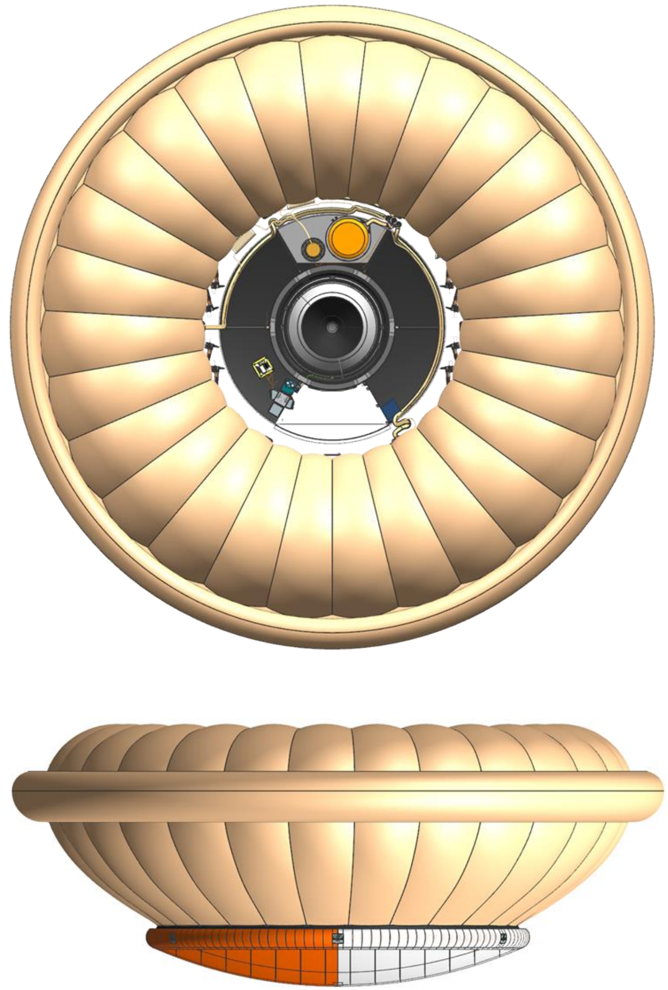
Questions?



Backup

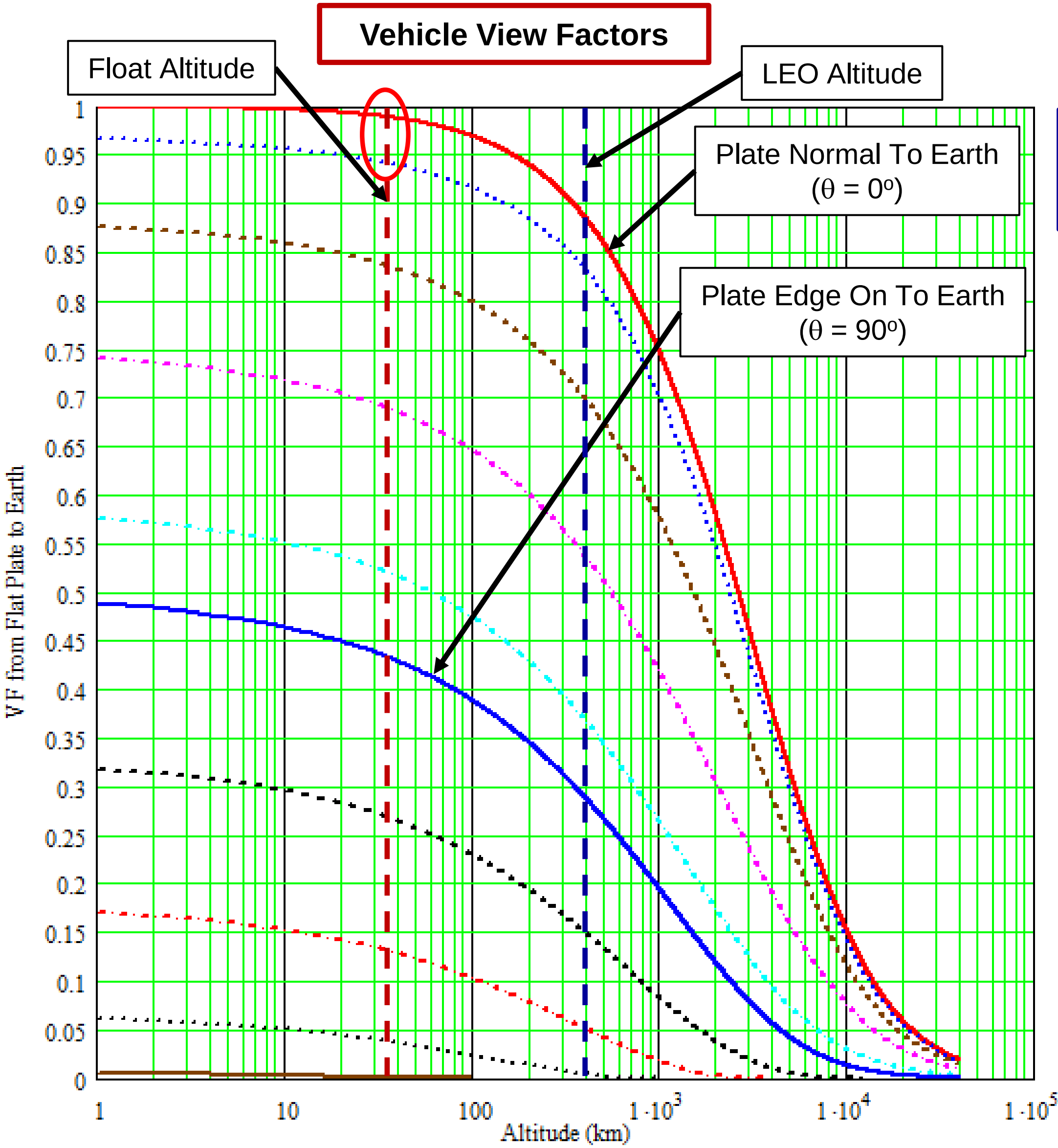


SIAD-R Deployed Configuration (6 m)

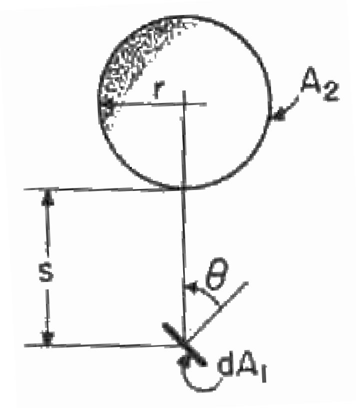


SIAD-E Deployed Configuration

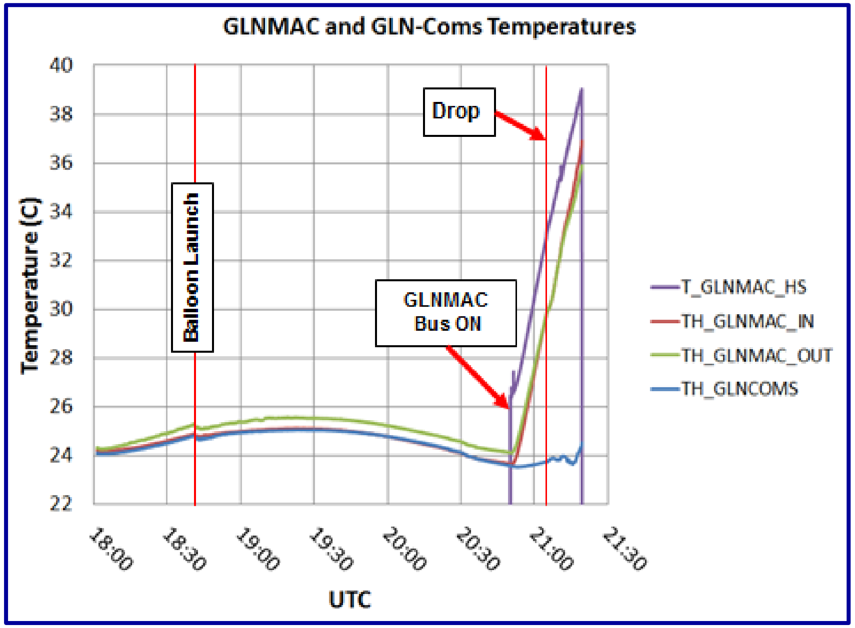
SFDT Thermal Environments (4/4)

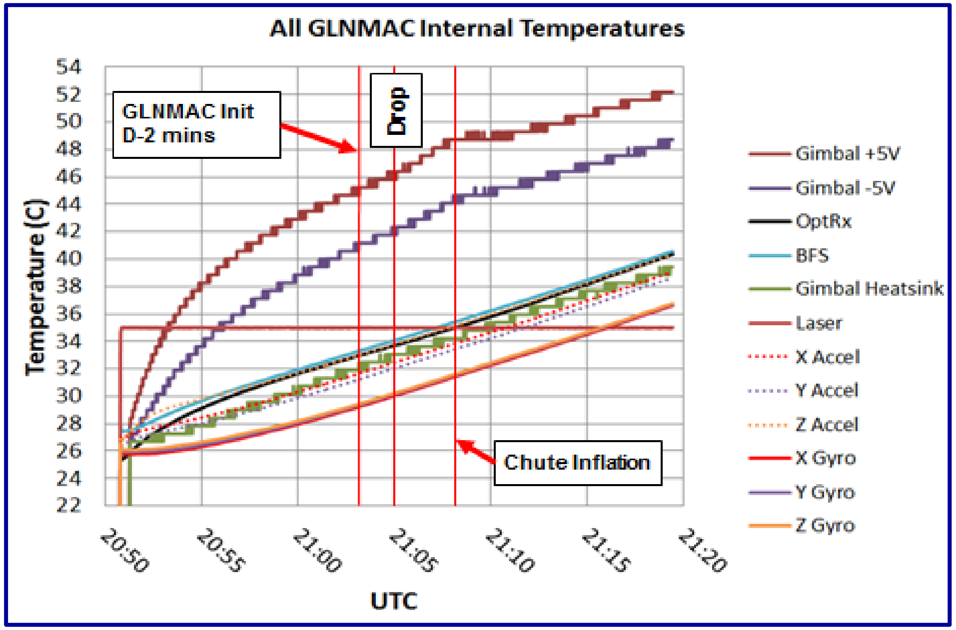


View Factors from Flat Plate to Earth as a Function of Attitude and Altitude



SFDT-1 Thermal Telemetry - GLNMAC





SFDT-1 Thermal Telemetry - Cameras